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STRONTIUM ISOTOPIC CONSTRAINTS ON THE GEOCHEMISTRY AND ORIGINS OF REGIONAL VEIN-FORMING FLUIDS IN THE SOUTHERN CANADIAN CORDILLERA

©

BY

AGNES M. KOFFYBERG

A Thesis
submitted to the Faculty of Graduate Studies and Research
in partial fulfilment of the requirements for the degree of
MASTER OF SCIENCE

Department of Geology

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Spring 1994

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UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled **Sr Isotopic Constraints on the Geochemistry and Origins of Regional Vein-forming Fluids in the southern Canadian Cordillera** submitted by Agnes M. Koffyberg in partial fulfilment of the requirements for the degree of Master of Science.

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Date December 30, 1993

ABSTRACT

In the southern Canadian Cordiliera, vein carbonates have been used to investigate the geochemistry and origins of hydrothermal fluid regimes. In particular, a systematic strontium isotopic investigation of regional vein carbonates from the Rocky Mountains to the Fraser Fault region has been conducted. In many areas, the strontium isotopic compositions reflect a host rock control, but in some cases, the values clearly indicate deposition from externally derived fluids.

Vein carbonates display a geographic variation in $^{87}Sr/^{86}Sr$ values across the southern Canadian Cordillera that decreases from east to west. Vein carbonates in the Proterozoic sequences of the Rocky Mountain Belt have Sr isotopic ratios that are generally > 0.730, and have been documented to be as high as 0.772. In the Paleozoic sequences in the Rocky Mountains and the eastern part of the Omineca belt, the Sr isotopic ratios range from 0.709 to 0.738. Sr isotopic compositions of vein carbonates decrease dramatically to the west of the Slocan Fault. Vein carbonates have $^{87}Sr/^{86}Sr$ values in the range of 0.705 to 0.707 in the Intermontane belt and the western portion of the Omineca belt. The Fraser Fault region exhibits Sr ratios in vein carbonates that are < 0.705. The east-west gradient is probably a direct reflection of the changing lithologies of crustal rocks in the Cordillera, from a carbonate dominated regime with older rocks in the eastern part to an increasingly volcanic regime with younger rocks in the western part.

In the Rocky Mountains, Sr isotopic data provide further evidence of the existence of two major fluid regimes, as documented by Nesbitt *et al.* (1993). In the Paleozoic sequences, Cambrian limestone units and replacement minerals have initial $^{87}Sr/^{86}Sr$ ratios that range from 0.7092 to 0.7119. In contrast, typical values for marine Cambrian carbonates range from 0.7083 to 0.7091 (Burke *et al.*, 1982). The higher $^{87}Sr/^{86}Sr$ ratios in the Rockies are indicative of a radiogenic fluid that has reset the original $^{87}Sr/^{86}Sr$ ratios of the carbonate rocks. Alteration has been documented on a scale of 100's of square kilometers.

A second fluid regime is recorded in the vein carbonates from the Proterozoic and Paleozoic sequences. In the Paleozoic units, vein carbonates have Sr isotopic compositions that range from 0.7091 to 0.7202. In the Proterozoic sequences, the Sr isotopic compositions range from 0.7308 to

0.7741. The Sr isotopic compositions of the veins formed from this fluid event are apparently derived from the host rocks.

Mineralized vein carbonates from the mesothermal gold deposit of the Cariboo district have Sr isotopic compositions that are significantly higher than the Sr ratios in the regional, barren vein carbonates. The stable isotope data in combination with the strontium data suggest that the mineralized zones of the Cariboo and Sheep Creek district contain radiogenic $^{87}Sr/^{86}Sr$ values relative to the regional hydrogeologic regime.

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I. INTRODUCTION

A. Purpose of Study

The Canadian Cordillera is an ideal place in which to examine the movement of crustal fluids. It spans a number of tectonic terranes, is host to a wide variety of igneous, metamorphic and sedimentary rocks, and consists of different structural styles, including compressional, extensional and strike-slip regimes. In addition, the area is well exposed and has been well mapped. These geological variations across the Cordillera allow for a thorough study of the role of hydrothermal fluids in relation to the tectonic history of the southern Canadian Cordillera.

Previous investigations of fluid regimes in the southern Canadian Cordillera have focused on the isotopic characteristics of whole rocks and vein minerals in deciphering fluid-rock interactions (Nesbitt, 1990; Nesbitt and Muehlenbachs, 1989a; Margaritz and Taylor, 1986). Hydrothermal fluids associated with granitic and metamorphic rocks have been characterized in terms of the origin of the fluids, temperatures of mineralizing fluids, extent of water-rock interactions and the degree of mixing of fluids from differing sources. Other work has focused on the stable isotopic characteristics of mineralized systems (eg. Xiong, 1993; Beaudoin *et al.*, 1992; Zhang *et al.*, 1989; Ohmoto and Rye, 1971) which have provided constraints to the genesis of such deposits as epithermal Au deposits, replacement and Ag-Pb-Zn vein systems.

As is the case with oxygen and hydrogen isotopes, changes in the $^{87}Sr/^{86}Sr$ ratios of hydrothermal carbonate reflect the extent of interaction between fluids and host rocks. As a solute in hydrothermal fluid regimes, strontium has been used as a tracer to determine fluid pathways. Strontium in hydrothermal fluids may be derived from mantle-derived rocks, from limestone sequences or from clastic sedimentary rocks. In zones of mineralization, strontium ratios of vein systems may suggest the possible source area of other solutes of economic importance such as gold. In the Canadian Cordillera, Sr analyses of hydrothermal carbonate have been reported for such areas of mineralization as the Bluebell Mine (in the southern Omineca Belt) and the MacDame mesothermal gold deposit in the Sylvester Allochthon (Changkakoti *et al.*, 1988; Nesbitt *et al.*, 1989a). No regional scale tracer studies of Sr isotopic compositions of hydrothermal fluids related to mineralized vein systems have been performed.

This study is the first to document regional scale Sr systematics of fluid regimes in the southern Canadian Cordillera, and indeed , in all of North America. This work attempts to investigate both regional fluid systems and mineralized vein systems, as recorded in vein carbonates. The main objectives of the study are: 1) to investigate the scale of fluid movement in regional vein systems by determining strontium ratios from vein carbonates; 2) to determine sources of strontium in hydrothermal fluids in various tectonic regimes; 3) to integrate information gained from strontium isotopes with stable isotope data on fluid regimes in the southern Canadian Cordillera; 4) to compare strontium isotopic compositions of mineralized veins (mesothermal Au, epithermal Au, Cu-Au skarn deposits) and barren veins consisting solely of quartz and carbonate minerals; 5) to determine the degree of fluid mixing within areas having a large degree of variability in strontium compositions, by comparing Sr concentrations to Sr isotopic ratios.

Vein carbonates are the primary minerals analysed in this study. The reasons for selecting carbonate minerals include: 1) Hydrothermal carbonates are abundant minerals in veins and are found in a variety of tectonic settings; 2) The $\delta^{18}O$ and $\delta^{13}C$ isotopic characteristics of quartz-carbonate veins in the southern Canadian Cordillera have been investigated (Nesbitt *et al.*, 1989b; 1993); 3) Carbonate minerals contain high proportions of strontium relative to rubidium. Consequently, the measured $^{87}Sr/^{86}Sr$ isotopic composition of the vein carbonates will not have increased significantly from the radioactive decay of ^{87}Rb since the time of formation of the vein. This allows us to make the assumption that initial $^{87}Sr/^{86}Sr$ ratios of the veins represent the $^{87}Sr/^{86}Sr$ ratios at the time of vein formation; 4) There is no strontium isotopic fractionation during precipitation from a fluid (Faure, 1986). Consequently, the measured Sr isotope ratio of the Sr-rich carbonate is indicative of the Sr isotopic composition of the hydrothermal fluid.

B. Location of Field Area

Vein carbonates analysed for this study are found within volcanic, metamorphic and sedimentary rocks located in the southern part of the

Canadian Cordillera. Host rocks from various regions have also been analysed. The sample localities span an area that lie between latitudes 49° to 53°N and extend from the Rocky Mountains to the Fraser River. The principle areas investigated are as follows:

1) The southern Rocky Mountain Belt between the Athabasca and the Bow rivers. Vein carbonates, limestones, dolostones, magnesites and ankerites were sampled from Proterozoic and Paleozoic strata.

2) The Omineca Belt. Sampling was focused on the vein carbonates hosted by the Paleozoic metasedimentary rocks of the Kootenay Arc and Quesnellia terrane in the southern part of the belt, and on veins from the Cariboo District in the central part.

3) The southern portion of the Intermontane Belt. Vein carbonates from the Nicola Group, the Cache Creek Group, the Spences Bridge Group and the Kamloops Group were sampled.

4) The Fraser River Fault system. Vein carbonates were sampled from the Bridge River Group, the Ladner Group and the Jackass Mountain Group.

5) Areas of mineralization. These include the Cariboo gold district (121° 30'W, 53° N), the Sheep Creek gold deposit (117° 20'W, 49° 10'N), the epithermal gold deposit from the Vault property near Penticton (119° 30'W, 49° 30'N), and the Phoenix Cu-Au skarn deposits of the Greenwood district (118° 30'W, 49° 10'N).

C. Previous Work - Sr Isotopes as Tracers

One of the first to investigate the use of Sr isotopes as tracers in hydrothermal systems was Reesman (1968). By analysing fluorite, barite and calcite gangue in several vein deposits in the western U.S., he concluded that the strontium isotopic compositions of hydrothermal minerals were primarily derived from the host rocks at the time of mineralization. Hedge (1974) analysed a number of deposits associated with Paleozoic sedimentary rocks, Precambrian rocks and Cenozoic igneous rocks in the western United States and reached a similar conclusion. Mineralized hydrothermal vein calcites and fluorites had similar $^{87}Sr/^{86}Sr$ values as those of contiguous igneous host rocks, suggesting that Sr was derived from the host rocks. However, as Hedge (1974) suggests, these results are generalizations and only accurate to a first approximation. For example, Reesman analysed gangue minerals from a number of Tertiary deposits from Colorado, Arizona and Montana and obtained a range of $^{87}Sr/^{86}Sr$ ratios of 0.705-0.711; yet analysed only one Tertiary host rock from the Telluride district, Colorado, which yielded a value of 0.709.

In contrast to these results, Casadevall and Ohmoto (1977), in their investigation of the isotopic compositions of gangue minerals in the Sunnyside mine, Colorado, concluded that Sr isotopic compositions could be derived from a source external to the host rocks. $^{87}Sr/^{86}Sr$ ratios were measured in hydrothermal barite, rhodochrosite, fluorite and gypsum from the epithermal gold deposit at the Sunnyside mine, Colorado. Gangue Sr values of 0.707-0.708 indicated a multiple source of Sr, including the Tertiary volcanics hosting the deposit (0.704-0.705) and the underlying Precambrian basement (0.710-0.720).

Other isotopic studies of ore deposits have yielded similar results. Carbonate and fluorite gangue analysed from Mississippi Valley-type deposits of the east-central United States yielded Sr compositions that were more radiogenic than the host carbonate rocks (Kessen *et al.*, 1981). The mineralizing fluids are thought to have inherited radiogenic strontium from silicates during their migration through the underlying sedimentary succession.

Norman and Landis (1983), in their study of the Pasto Bueno tungsten deposit, Peru, were able to show that the $^{87}Sr/^{86}Sr$ ratios of ore fluids, which ranged from 0.7058 to 0.7239, are the result of fluid mixing from differing source regions. Systematic variations in stable isotopes and Sr isotopic compositions indicated that selective leaching of Rb rich phases did not produce the higher Sr ratios.

Sr isotopes have been used as tracers in such ore deposits as mesothermal gold deposits (Böhlke and Kistler, 1986; Kerrich *et al.*,1987; King and Kerrich, 1988; Mueller *et al.*, 1991), porphyry deposits (Taylor and Fryer, 1983) and barite, fluorite and celestite deposits (Kesler *et al.*, 1981; Barbieri *et al.*, 1982). Sr isotopic compositions of subsurface fluids have been investigated by, among others, Stettler and Allegre, (1978), Stueber *et al.*, (1984), Chaudhuri *et al.*, (1987) and Connolly *et al.*, (1990).

Only one other study has documented Sr isotopic compositions of vein minerals on a scale of similar magnitude to this study. Baumann and Hofmann (1988) examined the $^{87}Sr/^{86}Sr$ isotopic compositions of gangue minerals such as barite, fluorite, calcite and gypsum from vein deposits throughout West Germany (Baumann and Hofmann, 1988). No direct relationship of vein Sr to the Sr isotopic composition of the host rock was observed, except for those veins hosted by limestone sequences.

D. Previous work in the Canadian Cordillera

In order to evaluate the role of magmatic and sedimentary rocks in affecting the Sr isotopic compositions of the fluids circulating through the crust, it is essential to know the range and geographical distribution of the strontium isotopic compositions of the rocks through which the fluids passed. There have been many studies that have used Rb-Sr systematics to determine the crystallization age of plutons in the Canadian Cordillera, which in turn have aided in deciphering its geological history. Table 1 shows initial $^{87}Sr/^{86}Sr$ ratios from various plutonic, volcanic, sedimentary and metamorphic rocks in the southern Canadian Cordillera, listed from east to west.

Work in the Rockies has focused on using Sr isotopic compositions to aid in deciphering the source of fluids for Mississippi Valley-type mineralization found in the Western Canada Sedimentary Basin, whose western edge is now within the Rocky Mountain belt. Medford *et al.* (1983a) analysed sulfides, carbonates and fluid inclusions from Pine Point, Northwest Territories in order to determine whether the mineralizing fluid responsible for the Pb-Zn mineralization was a diagenetic fluid derived from the Devonian seawater or a late stage hydrothermal fluid. Late stage dolomites and calcites from the mineralized zones had ratios of 0.7095 to 0.7143, in contrast to those of host carbonate rocks of the Presqu'ile Formation (0.7081-0.7089). Medford *et al.* (1983) interpreted the data to indicate that the ore fluids were in part derived from sedimentary rocks other than marine carbonates; however, they did not speculate as to the possible source or location of these rocks.

More recently, Qing and Mountjoy (1992) investigated the migration of basinal fluids in the Devonian Presqu'ile Reef and its relationship to the Pb-Zn mineralization at Pine Point, N.W.T. By sampling an area from northeastern British Columbia to Pine Point, a lateral distance of 400km, they observed a decrease in $^{87}Sr/^{86}Sr$ ratios of sparry dolomite cements, from a value of 0.7106 in northeastern British Columbia to 0.7081 at Pine Point. Citing

Table 1 Compilation of Sr isotope data for selected lithologies in the southern Canadian Cordillera

Area-Lithology	Rock Type	($^{87}Sr/^{86}Sr$) ±2σ (x10^{-5})	Age (Ma)	Interpretation	Source
Kootenay Arc					
Nelway Fm	metasediments	0.71018±27	557±50	sedimentation	Ghosh, 1986
Active Fm (Paleozoic)	metasediments	0.71662±34	160±8	metamorphism	Ghosh, 1986
Milford Gp (Paleozoic)	qtz-bi-musc schist	0.71161±38	262±46	metamorphism	Ghosh, 1986
	gt-staur-schist	0.70922±162	264±12	metamorphism	Ghosh, 1986
Bluebell Mine	fl.incl. in gangue	0.7143	19±6	mineralization	Changkakoti et al., 1988
Raft batholith	granodiorite	0.70505±10	164±2	crystallization	Brandon, 1992
Galena Bay batholith	monzonite	0.7056±2	157±2	crystallization	Parrish and Armstrong, 1987
Whatshan batholith	granodiorite	0.70432±9	150±3	crystallization	Brandon, 1992
Fry Creek batholith	granitoids	0.70778±14	115±7	crystallization	Brandon, 1992
White Creek batholith -core	granitoid	0.7250±9	115±5	crystallization	Wanless et al., 1968
White Creek batholith -core	granodiorite	0.71020±5	106±1	crystallization	Brandon, 1992
-rim	qtz monzodiorite	0.7073±6	106±1	crystallization	Brandon, 1992
Horsethief Creek batholith	granitoids	0.70831±20	109±14	crystallization	Brandon, 1992
Bugaboo batholith	granitoids	0.70773±12	107±1	crystallization	Brandon, 1992
Baldy batholith	granitoids	0.7054	98±2	crystallization	Calderwood et al., 1990
Slide Mountain terrane					
Fennell Formation	basalts	0.7025-0.7030	300	approx. age of crystallization	Smith, 1986

Area-Lithology	Rock Type	$(^{87}Sr/^{86}Sr)$	Age (Ma)	Interpretation	Source
Monashee Complex					
Frenchman Cap Core gneiss	gneiss	0.700±2	2206±117	assimilation of core gneiss	Armstrong et al., 1991
Quesnellia					
Slocan Gp	metasediments	0.70800±4	247±6	inherited Sr during sedimentation	Ghosh, 1986
Rossland Gp	volcanics	0.7033 to 0.7040	170	approx. age of crystallization	Beddoe-Stephens & Lambert, 1981
Ymir Gp	metasediments	0.70644±36	250±16	inherited Sr during sedimentation	Ghosh, 1986
Nemo Lakes belt, Valhalla Range					
Late Paleozoic seds	metasediments	0.7054±9	516±44	deposition	Parrish, 1981
Early Paleozoic ±Traissic seds	metasediments	0.7063±11	228±42	deposition	Parrish, 1981
Grand Forks gneiss	paragneiss	0.707±5	1675±397	deposition or metamorphism	Armstrong et al., 1991
Okanagan Lake area					
Whiteman Creek stock	monzonites	0.70515±15	59±2	crystallization	Medford et al., 1983b
composite near Whiterocks Mtn	granites	0.7039±1	150±5	crystallization	Medford et al., 1983b
Okanagan composite batholith	granite	0.70415±17	156±6	crystallization	Peto and Armstrong, 1976
Vaseaux Formation	paragneiss	0.704±5	2059±586	crustal residence age	Armstrong et al., 1991

Area-Lithology	Rock Type	($^{87}Sr/^{86}Sr$)	Age (Ma)	Interpretation	Source
Kamloops Gp	volcanics	0.7038 to 0.7048	50	approx. age of crystallization	Smith, 1986
Nicola Gp	volcanics	0.7025 to 0.7042	220	approx. age of crystallization	Smith, 1986
Nicola Gp	volcanics	0.7034 to 0.7047	-	inherited radiogenic Sr	Preto et al., 1979
Nicola Gp	limestones	0.7074, 0.7076	-	Triassic limestone	Preto et al., 1979
Cache Creek Gp	basalts	0.7041 to 0.7053	300	approx age of crystallization	Smith, 1986
Spences Bridge Gp	volcanics	0.70334±8	115±35	crystallization	Smith, 1986
Spences Bridge Gp	volcanics	0.70379±4	112±5	crystallization	Preto et al., 1979
Kingsvale Gp	volcanics	0.70379±4	112±10	crystallization	Preto et al., 1979
Thuya batholith	granite	0.70435±10	200	crystallization	Preto et al., 1979
Thuya batholith	granite	0.7042	184±4	crystallization	Calderwood et al., 1990
Iron Mask batholith	alkaline granite	0.7035±1	200	crystallization	Preto et al., 1979
Guichon batholith	granite	0.7034±1	205±10	crystallization+ mineralization	Preto et al., 1979
		Fraser Fault Region			
Bridge River Group	schists	0.70500±2	~152	metamorphism	Leitch et al., 1991
Bralorne Intrusions	diorite, granite	0.7033±1	270	crystallization	Leitch et al., 1991

Area-Lithology	Rock Type	$(^{87}Sr/^{86}Sr)$	Age (Ma)	Interpretation	Source
Albitite dikes	granitic	0.70336±10	102±10	crystallization+ max. age of mineralization	Leitch et al., 1991
Zoa complex	qtz diorite	0.70331±5	153±10	crystallization	Greig et al., 1992
Eagle Plutonic complex	tonalite , gneiss	0.70365±2	111±2	crystallization	Greig et al., 1992
Fallslake Plutonic suite	granodiorite	0.70400±8	102±2	crystallization	Greig et al., 1992
Needle Peak Pluton	monzogranite	0.70363±12	41±8	emplacement	Greig et al., 1992
Coquihalla volcanic complex	volcanics	0.7037	22±4	crystallization	Bergman and Armstrong, 1980
Summary for Volcanic and Plutonic Rocks					
Omineca belt					
Jurassic	granitoids	0.704-0.710			Armstrong, 1988
mid-Cretaceous	granitoids	>0.707, some >0.720			Armstrong, 1988
Cenozoic	granitoids	0.704-0.710			Armstrong, 1988
Intermontane					
Mesozoic	granitoids	0.703-0.707			Armstrong, 1988
Cenozoic	granitoids	0.704-0.707			Armstrong, 1988
southern Coast Plutonic belt	granitoids	<0.704			Armstrong, 1988
Insular belt- Vancouver Island	granitoids	<0.704			Armstrong, 1988

supporting evidence from $\delta^{18}O$ values and homogenization temperatures, they suggested a regional eastward migration of hot, saline dolomitizing fluids. These fluids were responsible for development of saddle dolomite and the Mississippi Valley-type mineralization at Pine Point.

Further west in the Omineca belt, Changkakoti *et al.* (1988) determined the Sr isotopic composition of fluid inclusion waters from the Bluebell Pb-Zn deposit in the Kootenay Arc in order to define the timing of mineralization. They obtained an isotopic date of 19.2 ± 5.9 Ma as the age of the latest mineralization and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7143. Two host marbles barren of mineralization yielded a Sr isotopic composition of 0.7117, whereas two mineralized marbles yielded values of 0.7143. They concluded that the source of the radiogenic strontium was in fact the marble and that the barren samples had either completely different initial ratios or had incompletely homogenized with the fluids.

Sr isotopic compositions of metasedimentary rocks of the southern Kootenay Arc were obtained by Ghosh (1986). An age of sedimentation of 557±50 for the metasedimentary rocks of the Cambrian Nelway Formation was obtained, with an initial $^{87}Sr/^{86}Sr$ of 0.71018±27. A metamorphic age of 160±8, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.71662±34 was obtained for the Lower Ordovician Active Formation. Ghosh (1986) also obtained a metamorphic age of 263 Ma (initial $^{87}Sr/^{86}Sr$= 0.7092- 0.7116) for the metasedimentary rocks of the Carboniferous Milford Formation.

The major Rb-Sr work other than that pertaining to sedimentary rocks and ore deposits relates to sources and evolution of magmatic rocks of the accreted terranes in the Canadian Cordillera. Amstrong (1988) compiled Rb-Sr dates and initial $^{87}Sr/^{86}Sr$ ratios of Mesozoic and Cenozoic igneous rocks that occur throughout the Canadian Cordillera. Initial $^{87}Sr/^{86}Sr$ ratios of igneous rocks are used to infer the degree to which continental crust is incorporated into the magma. Initial $^{87}Sr/^{86}Sr$ ratios in the range 0.703 to 0.704 are typical of magmas from oceanic and island-arc settings (Faure, 1986). Ratios > 0.706 exist in magmas derived from or incorporating continental crust (Armstrong, 1988). The transitional zone (0.704 - 0.706) marks the transition in magmas derived from the old Precambrian craton to the younger Phanerozoic crust. Using Sr data, Armstrong (1988) was able to identify the regions in the Cordillera that are underlain by Precambrian and Phanerozoic basement. In doing so, he noted systematic variations in the initial

Sr ratios of the magmatic rocks in the Cordillera. The overall groupings of initial $^{87}Sr/^{86}Sr$ ratios for plutons and volcanic rocks as contoured by Armstrong (1988) are listed in Table 1. Magmatic rocks with an initial $^{87}Sr/^{86}Sr \geq 0.704$ indicate that the magmas are in part derived from crustal sources. For Mesozoic volcanic and plutonic rocks, the 0.704 contour line is approximately equivalent to the Okanagan Valley region, implying that this was also the western limit of the old cratonic crust. The Cenozoic 0.704 line is located 75km farther to the west than the 0.704 line of Mesozoic rocks (Armstrong and Ghosh,1990). Plutonic rocks of the Coast Plutonic belt have initial ratios $\leq$ 0.704, regardless of their age. Volcanic and plutonic rocks of the Insular belt are similarly $\leq$ 0.704.

Many of the plutonic and volcanic rocks that either host the carbonate veins of this study or occur proximal to them have been analysed in detail. Brandon (1992) analysed the Sr isotopic compositions of the Bugaboo, Fry Creek and Horsethief Creek batholiths, situated in the southern part of the Omineca belt (Brandon, 1992; Brandon and Lambert, 1993). These batholiths have an initial $^{87}Sr/^{86}Sr$ value of 0.70773 ±12, 0.70778 ±14 and 0.70831 ±20, respectively. These high initial $^{87}Sr/^{86}Sr$ ratios led Brandon (1992) to suggest that anatexis of Precambrian basement gneisses had produced batholiths of these isotopic compositions.

The Sr systematics of the volcanic rocks located in the Intermontane Belt were investigated by Smith (1986) and others. Smith (1986) was unable to obtain a precise initial $^{87}Sr/^{86}Sr$ ratio or an age of crystallization for basalts from various units such as the Triassic Nicola Group and the Cache Creek Group, because low grade metamorphism had altered the Rb-Sr systematics within the rocks. Consequently, he assumed a crystallization age for each rock suite in order to obtain a range of initial $^{87}Sr/^{86}Sr$ values. Initial $^{87}Sr/^{86}Sr$ values that varied from 0.7041 to 0.7053 and 0.7025 to 0.7042 for the volcanic rocks of the Cache Creek Group,and the Nicola Group, respectively, were calculated. Smith (1986) also obtained a range in initial $^{87}Sr/^{86}Sr$ values from 0.7038 to 0.7048 for the volcanic rocks of the Tertiary Kamloops Group. The variation in $^{87}Sr/^{86}Sr$ for these volcanic rocks was interpreted as heterogeneity of the Sr isotopic composition in the mantle (Smith, 1986). Basalts from the Late Cretaceous Spences Bridge Group gave an initial $^{87}Sr/^{86}Sr$ of 0.70334±8 which is in agreement with the value of 0.70379±4 obtained by Preto *et al.* (1979).

Plutonic and metasedimentary rocks in the Fraser Fault region have been analysed by Leitch *et al.* (1991) and Greig *et al.* (1992). Plutonic rocks in the region such as the Eagle Plutonic Complex and the Zoa Complex, have initial $^{87}Sr/^{86}Sr$ ratios that range from 0.703 to 0.704 (Greig *et al.*, 1992). Bridge River Group schists have initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.7050 to 0.7060. The Sr systematics of these rocks have been reset by Jurassic to Eocene metamorphic episodes (Leitch *et al.*, 1991).

II. TECTONIC SETTING AND EVOLUTION

A. Introduction

In order to understand the influence of tectonics and the role of structural style in the development and movement of large volumes of fluid, it is necessary to examine briefly the major tectonic units and the evolution of the Canadian Cordillera. Emphasis is placed on the southern portion of the Canadian Cordillera and on terranes which encompass the field area of study.

B. Regional Geology

The Canadian Cordillera has been divided into five physiographic belts: Rocky Mountain belt, Omineca Crystalline belt, Intermontane belt, Coast Plutonic belt and Insular belt (Monger *et al.*, 1982). The location of these belts, along with the area of study are shown on Figure 1.

The Rocky Mountain belt contains sedimentary rocks that range from Proterozoic to Tertiary in age. Middle Proterozoic rocks include the Purcell Supergroup in the southern part of the belt and the Mackenzie Mountains assemblages in the northern part. These strata consist of clastic and carbonate sediments with local mafic volcanics (Monger, 1989). Late Proterozoic rocks include the Miette Group, which is part of the Windermere Supergroup, and consist of sequences of grit and shale, with minor volcanics and carbonates. These sedimentary rocks appear to have been deposited at a time of rifting of the western continental margin. Paleozoic sequences were deposited in a passive margin setting on the edge of the North American craton. Platformal carbonates from various formations including the mid-Cambrian Cathedral Formation were deposited in a relatively shallow inshore basin along the edge of the continent. Deeper water argillaceous shales of the Chancellor Formation were deposited further west (Gabrielse and Yorath, 1989). A sharp platform-to-basin transition occurs at the boundary between the eastern and western Main Ranges of the southern Rocky Mountains (Stewart, 1989). From the late Jurassic until early Tertiary time, the units were compressed and uplifted onto the western edge of North America, forming a

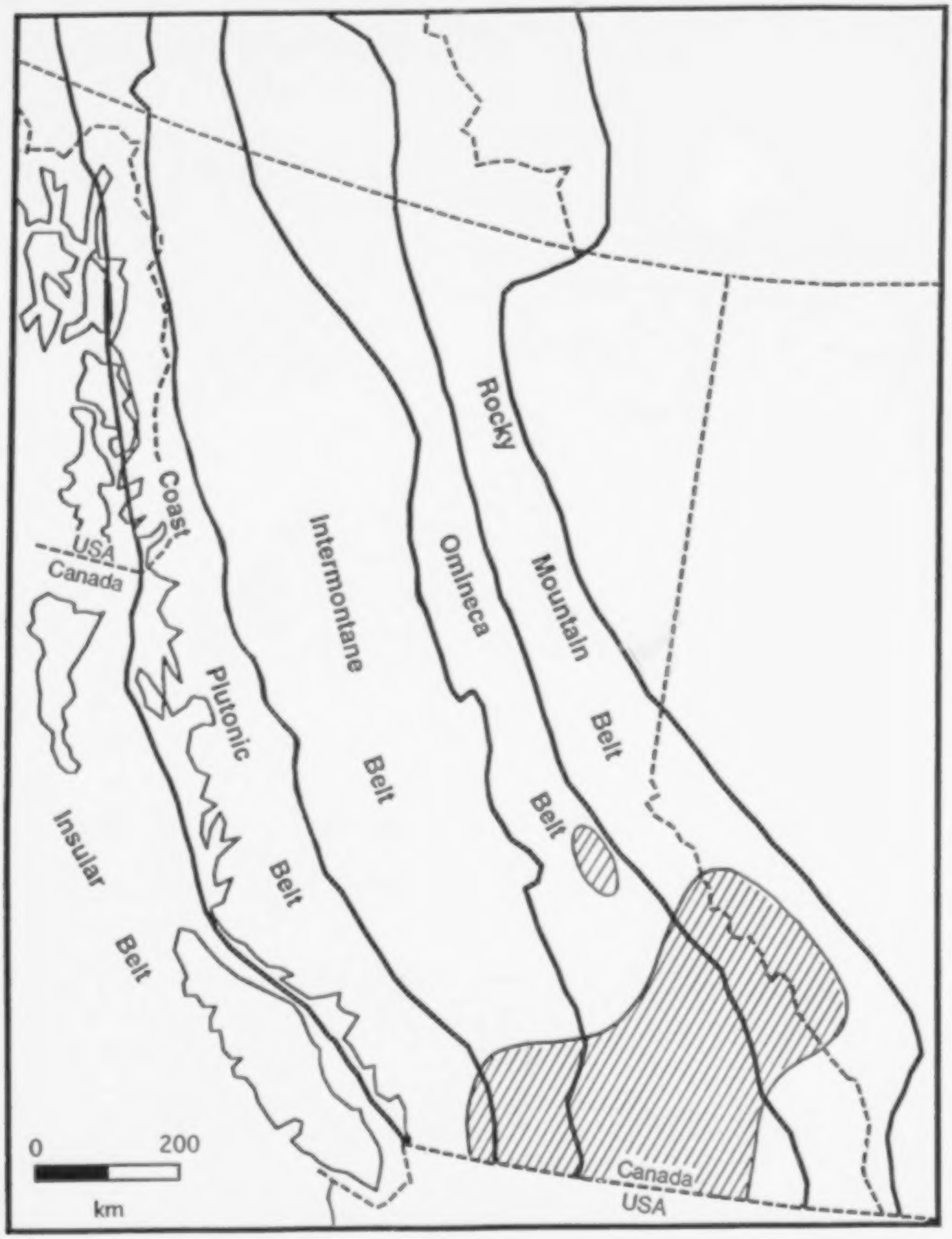

Rocky
Mountain
Belt
Omineca
Belt
Intermontane
Belt
Coast
Plutonic
Belt
Insular
Belt
USA
Canada
0
200
km
Canada
USA

Figure 1 Map of the physiographic belts of the Canadian Cordillera (modified after Monger, 1984) showing location of study area.

series of east-verging thrust slices (Monger, 1982). Overall shortening and eastward displacement is over 200 km in the southern part of the Rocky Mountain belt (Gabrielse *et al.*, 1991). The mountain building resulted in a westerly derived source for the clastic strata that formed during this period. Regional metamorphism in the Rocky Mountain belt in general corresponds to stratigraphic changes. Greenschist facies rocks occur in Precambrian sequences, prehnite-pumpellyite facies belong to Paleozoic and some Mesozoic strata, and zeolite facies rocks are usually of Mesozoic age (Greenwood *et al.*, 1991).

The Paleozoic carbonate platform is host to a number of Mississippi Valley-type deposits. Important Pb-Zn mineralization include Pine Point, N.W.T., in the Devonian Presqu'ile Reef, and the Kicking Horse and Monarch mines within the Middle Cambrian Cathedral formation (Dawson *et al.*, 1991).

The Omineca belt is a plutonic and metamorphic welt which separates continental sediments of the Rocky Mountain belt from allochthonous terranes to the west (Monger, 1989). It contains rocks of ancestral North America, as well as pericratonic (eg. Kootenay) and accreted terranes (eg. Slide Mountain). The amalgamation and accretion of the composite Terrane 1 to the continental margin during the late Mesozoic and early Tertiary caused intense deformation, uplift and metamorphism in the assemblages, along with plutonism. Metamorphic grade in the Omineca reached upper amphibolite facies. Extensional tectonism in the Eocene resulted in the formation of metamorphic core complexes, and numerous, low angle normal faults, such as the Columbia River and the Slocan Lake faults (Parrish *et al.*, 1988).

The Omineca belt contains several mesothermal Au deposits including the Cariboo district in the Barkerville subterrane and the Sheep Creek district in the southern part of the Kootenay Arc. The southern extensional zone also hosts the Ag-Pb-Zn vein and replacement deposits of the Slocan Camp (Beaudoin *et al.*, 1992).

The Intermontane belt is comprised of allochthonous terranes containing rocks of island arc and oceanic basin lithologies, ranging in age from upper Paleozoic to mid-Mesozoic. The island arc terranes of Quesnellia and Stikine, and the oceanic terranes of Slide Mountain and Cache Creek amalgamated to form a large composite terrane, Terrane I, prior to being accreted to the western margin of North America (Monger, 1989) in the Middle Jurassic. Metamorphic rocks reached no higher grade than greenschist facies, in contrast to rocks from adjacent belts (Gabrielse *et al.*, 1991). Episodic calc-alkaline volcanism and plutonism occurred throughout the Mesozoic and early Cenozoic (Armstrong, 1988).

Associated with the emplacement of the Early Jurassic plutons are numerous skarn deposits. The southern Intermontane belt is host to OKA Au-bearing skarns east of Peachland, Au skarns in the Hedley camp, and the Cu-Au skarns of the Phoenix deposit in the Greenwood area. Epithermal Au-Ag deposits such as Dusty Mac and the Vault property are associated with the extensional Okanagan Valley fault.

The Fraser fault system comprises the contact between the Intermontane belt and the Coast Plutonic belt. It consists of a number of large strike-slip faults, such as the Pasayten, Fraser and Hozameen-Yalakom faults, of Cretaceous to Eocene age. Movement along the faults is estimated to be at least 150 km, causing the lateral displacement of westerly terranes northward (Monger, 1989).

The Coast Plutonic belt is dominated by highly metamorphosed calc-alkaline plutonic rocks of mainly Cretaceous and Tertiary age (Armstrong, 1988). In addition it contains sedimentary and volcanic rocks, metamorphosed up to amphibolite grade. The belt formed during and after the collision of Terrane II, a composite block consisting of allochthonous terranes, to the continental margin (Monger, 1989).

The Insular belt consists of assemblages of volcanic, carbonate and clastic rocks with minor plutons belonging to the allochthonous Wrangellia, Alexander and Gravina-Nutzotin terranes. These terranes amalgamated to form Terrane II by the late Jurassic, which accreted onto the western margin during mid-Cretaceous time (Monger *et al.*, 1982).

In summary, from the mid-Proterozoic to Early Paleozoic time, the western margin of the continent underwent extensional tectonism. Deposition of easterly derived sediments occurred on a passive margin setting in Paleozoic time. From the end of the Jurassic until Eocene time, compressional tectonism dominated the evolution of the Cordillera. This resulted in accretion of the allochthonous composite terranes of the Intermontane and the Insular belts, the formation of granitic and metamorphic belts of the Coast Plutonic and Omineca belts and the development of thrust sheets of the Rocky Mountain belt. Subsequent to accretionary events, right-lateral strike slip faulting (Fraser faults, Tintina and Northern Rocky Mountain Trench faults) in late Cretaceous-early Tertiary time caused displacement of terranes northward (Monger, 1984). The southern Omineca belt experienced extensional tectonism in Eocene time, resulting in normal faulting and the unroofing of core complexes.

III. ANALYTICAL METHODS

A. Strontium Isotopic Analysis

About one hundred and twenty carbonate samples were analysed for Sr isotopic values. The veins sampled range from cm to meters in length and are typically less than 15cm wide. Chips of vein carbonate were ground in a stainless steel mortar. Some carbonate samples contained a quantity of quartz intergrown with the carbonate fraction. The quartz was ground up and homogenized with the carbonate and a sample size of approximately 0.2 g was measured for dissolution.

Pure calcite samples were dissolved directly in concentrated HNO_3. Dolomite and ankerite were dissolved by adding 6N HCl and heating for at least 2 hours. The chloride solution was then converted to a nitrate solution with repeated addition of HNO_3 and evaporation to incipient dryness. Impure samples containing quartz, clays or minerals such as sulfides were initially dissolved in 6N HCl to ensure that the only source of strontium would be from the carbonate fraction. The residue was removed by centrifuging and the supernatant was brought to dryness and converted from chloride to nitrate. Silicates were digested using an HF/HNO_3 mixture, converted to nitrate and the same procedure was followed. Strontium was concentrated using $Ba(NO_3)_3$ co-precipitation. Purification of Sr from other cations was achieved by cation exchange techniques, using DOWEX AG50-W-X8 resin (100-200 mesh).

Strontium was loaded as a chloride onto the side arm of a double rhenium filament and the $^{87}Sr/^{86}Sr$ ratios were measured on a VG MM30 mass spectrometer. For isotope dilution analyses on the host rock samples, a mixed Rb-Sr spike solution enriched in ^{87}Rb and ^{84}Sr was added prior to dissolution.

Blanks were less than 8 ng with sample sizes approximately 200 mg. Ratios were normalized to $^{86}Sr/^{88}Sr$ ratio of 0.1194. Reproducibility of $^{87}Sr/^{86}Sr$ ratios was monitored by repeated analysis of the NBS 987 Sr standard. Twenty-two analyses gave a mean $^{87}Sr/^{86}Sr$ of 0.710259 ± 0.000016 (2σ) and range from 0.710160 to 0.710327. Precision of individual runs was usually better than ± 0.00007 (2σ). Duplicate analysis was performed on a few samples to ensure that the powders had been thoroughly homogenized. Overall reproducibility is better than ±0.00005 (2σ).

Although carbonates in general have low rubidium contents, Sr and Rb concentrations were determined by X-ray fluorescence to verify low Rb/Sr values. Rock chips were powdered using a SPEX 8000-II mixer/mill to ensure homogeneity and a fine grain size. Pressed powder pellets were prepared and Sr, Rb, as well as Ca, Mg, Fe and Mn were analysed on a Siemens XRF spectrometer at Sherritt Inc., Fort Saskatchewan, Alberta. Results are listed in Appendix I. Rb concentrations were generally less than 10 ppm. Sr abundances ranged from ~70-50000 ppm. In the case of five samples, Rb/Sr concentrations were large enough, given the approximate age of the veins and the limestones, to have an effect on the initial $^{87}Sr/^{86}Sr$ values. Calculations used to compute the $^{87}Sr/^{86}Sr$ ratios of these samples are given in Appendix II. The rest of the vein carbonates and limestones had negligible Rb; with the result that the measured ratios were taken as the $^{87}Sr/^{86}Sr$ ratios at time of vein formation.

Because of the small difference in mass between ^{87}Sr and ^{86}Sr, there is negligible isotopic fractionation during precipitation from a fluid (Faure, 1986). Consequently, the measured Sr isotope ratio of the Sr-rich carbonate is indicative of the Sr isotopic composition of the hydrothermal fluid. Selected silicate host rocks were analysed in order to compare Sr ratios of the host rock to those of the veins. Initial $^{87}Sr/^{86}Sr$ ratios of silicate rocks were calculated using measured Rb/Sr ratios, a Rb decay constant of 1.42×10^{-11} (Steiger and Jäger, 1977) and an approximate age of vein formation. In some cases, the age is known (eg. Eocene age for mineralized veins in the Slocan, Beaudoin *et al.*, 1992), otherwise it was inferred from structural relationships.

B. Stable Isotopic Analysis

Powdered carbonates were dissolved using pure phosphoric acid at 25°C using the method described by McCrea (1950). $^{18}O/^{16}O$ ratios and $^{13}C/^{12}C$ ratios in the CO_2 gas were analysed on a VG 602D Micromass mass spectrometer. The results are presented in the normal δ-notation (‰) relative to the SMOW standard for oxygen and the PDB standard for carbon. Results are generally reproducible to within ±0.2‰ and ±0.1‰ for $\delta^{18}O$ and $\delta^{13}C$ respectively.

IV. STABLE ISOTOPE GEOCHEMISTRY

A. Introduction

In this study, oxygen and carbon isotopes are used as chemical tracers to study the sources of vein-forming fluids in a variety of tectonic settings and mineralized areas within the Canadian Cordillera. Oxygen isotopes have been used to indicate fluid/rock interaction. Carbon isotopes have been used to identify the source of carbon in the vein carbonates. As a solute in hydrothermal fluids, carbon can be derived from a variety of sources. Carbon may originate from magmatic rocks, from organic material contained within carbonaceous sediments and metamorphic rocks or from dissolution or decarbonation reactions of carbonate rocks (Ohmoto and Rye, 1979).

$\delta^{18}O$ and $\delta^{13}C$ data of regional vein carbonates sampled across the southern Canadian Cordillera are presented in Table 2. Included are $\delta^{18}O$ and $\delta^{13}C$ values from quartz-carbonate veins obtained by Nesbitt *et al.* (1993) from the Rocky Mountain belt. The results presented here are compared to the oxygen and carbon results obtained by Nesbitt *et al.* (1993), which are predominantly from quartz-carbonate veins collected throughout the southern Canadian Cordillera.

Within the Rocky Mountains, two distinct fluid events have been recognized by Nesbitt *et al.* (1993), who has defined fluid patterns based on information gathered from $\delta^{18}O$, δD, $\delta^{13}C$ data, fluid inclusions and structural relationships. An early, preorogenic fluid event appears to have occurred prior to thrusting and uplift of the Rocky Mountains. This fluid event is best recorded in replacement minerals that formed within the Paleozoic sequences in the Main and Western Ranges. These saline fluids migrated from the western shale units eastward through the carbonate units prior to thrusting of the Rocky Mountains, causing alteration of the limestone units over an extensive region in the Rocky Mountains (Nesbitt and Muehlenbachs, 1993). Saddle dolomites, magnesite alteration at Mt. Brussilof, and Mississippi Valley-type mineralization at the Kicking Horse and Monarch mines were deposited from these basinal brines. Cambrian limestones to the east of the shale/carbonate transition have also been isotopically altered.

Table 2 Oxygen and carbon isotopic data for regional carbonate veins

Unit and Sample[1]	Mineral	$\delta^{18}O$ ‰SMOW	$\delta^{13}C$ ‰PDB
ROCKY MOUNTAIN BELT[2]			
Preorogenic Fluid Event			
RB 624	dolomite	13.5	-1.1
RB 625	dolostone	14.1	-0.8
RB 659	limestone	11.6	+0.1
RB 695	limestone	20.3	-0.6
RB 706	limestone	14.4	+0.7
RB 732	dol. breccia	12.3	-2.7
RB 733	dol. breccia	13.5	-1.2
Syn- to Postorogenic Fluid Event			
Miette Group			
RB 563	calcite	13.8	-7.3
RB 569	calcite	13.7	-7.4
RB 570	calcite	14.6	-12.0
RB 573	calcite	12.0	-13.2
RB 576	calcite	13.1	-12.9
RB 604	calcite	13.6	-7.2
RB 636	ankerite	15.8	-11.6
RB 639	calcite	12.3	-11.3
RB 641	calcite	14.1	-7.5
RB 671	calcite	16.7	-2.7
RB 754	limestone	14.4	-8.3
RB 755	limestone	14.4	-7.5
Paleozoic Carbonate Sequences			
RB 678	calcite	21.2	-0.5
RB 679	calcite	19.0	-1.0
RB 682	calcite	12.7	-10.5
RB 710	limestone	16.7	-0.4
Paleozoic Clastic Sequences			
RB 257	calcite	16.2	+0.2
RB 472b	calcite	18.3	-0.2
RB 477	calcite	19.4	+0.5
RB 651	calcite	16.0	-1.9
RB 662	calcite	17.9	-1.5
AK91-1	calcite	17.2	-1.5
AK91-2	calcite	21.3	-1.6
AK91-3	calcite	18.6	-0.4
OMINECA BELT			
Cariboo District			
C45	calcite	1.4	-1.9
C46	calcite	17.4	-3.4
C47a	marble	23.6	-0.8
C48	limestone	23.3	-0.1
C48a	calcite	17.9	-0.8
Slide Mountain Group			
SM2	calcite	12.6	-7.4
SM3a	limestone	17.6	-0.7

Unit and Sample	Mineral	$\delta^{18}O$ ‰SMOW	$\delta^{13}C$ ‰PDB
SM3b	calcite	13.3	-2.1
Kootenay Arc			
AK91-4	Fe calcite	15.8	-2.6
AK91-5	Fe calcite	17.5	-3.8
AK90-7	Fe calcite	15.5	-4.8
AK90-8	calcite		
AK90-9	Fe dolomite	14.6	-6.5
Slocan Group			
AK91-27	calcite	12.0	-6.0
AK91-27a	limestone	8.0	-6.5
AK91-28	calcite	14.8	-5.1
AK91-30	calcite	6.6	-7.3
Rossland Group			
AK90-13	calcite	10.6	-5.6
INTERMONTANE BELT			
Nicola Group[3]			
AK91-6	calcite	14.7	-9.2
AK91-7	calcite	14.4	-4.7
AK91-7a	limestone	13.4	-7.2
RB 340	dolomite	6.1	-4.2
AK90-38	calcite	5.5	-5.7
Late Paleozoic Sequence			
AK91-9	Fe calcite	2.2	-4.0
Tertiary Volcanics			
AK91-10	calcite	6.4	-8.6
AK91-11	calcite	8.7	-6.2
X-19	calcite	7.4	-5.1
X-118	calcite	5.9	-5.9
X-38b	calcite	4.0	-5.8
Cache Creek Group			
RB 358	calcite	11.0	1.6
AK91-24	calcite	10.5	-6.3
AK91-25	calcite	7.4	-5.0
AK91-26	calcite	2.3	-4.7
Spences Bridge Group			
AK91-21	calcite	6.5	-7.4
AK91-22	calcite	8.5	-10.4
AK91-23	calcite	4.0	-6.7
Fraser Fault Region			
Jackass Mtn Group			
AK91-16	Fe calcite	12.9	-8.8
AK91-17	calcite	9.8	-8.5
AK91-18	calcite	14.1	-11.3
AK91-19	calcite	15.3	-8.1

Unit and Sample	Mineral	$\delta^{18}O$ ‰SMOW	$\delta^{13}C$ ‰PDB
Ladner Group			
AK90-36	calcite	13.3	-8.3
Bridge River Group			
AK91-12	calcite	16.2	-8.6
AK91-13	calcite	17.1	-10.1
AK91-14	dolomite	20.4	-4.4
AK91-15	calcite	15.1	-5.7
RB 381	calcite	15.3	-9.2

Notes:

[1] Sample in bold type indicates analysis of host rock.

[2] Oxygen and carbon data from the Rocky Mountains and the Cariboo district is from Nesbitt and Muehlenbachs (1993) and Nesbitt *et al.*, (1989).

[3] The area of sampling covers both the Omineca Belt and the Intermontane Belt.

A second regional fluid event occurred during or after uplift of the Rocky Mountains (Nesbitt *et al.*, 1993). These syn- to postorogenic fluids produced quartz and quartz-carbonate veins, which are found throughout the Rocky Mountains in rocks of differing ages, differing lithologies and differing grades of metamorphism. The veins are generally subvertical and cut across folds, and represent circulation of meteoric water through the Proterozoic and Phanerozoic sequences. Vein chemistry in general, reflects that of the host lithology.

B. Oxygen Isotope Data

Figure 2 compares the range of $\delta^{18}O$ values in vein carbonates obtained from the Rocky Mountains to the $\delta^{18}O$ values from the Omineca belt to the Fraser Fault region. $\delta^{18}O$ values of vein carbonates in the Rocky Mountain belt are more uniform than the $\delta^{18}O$ values occurring in vein carbonates to the west of the Rocky Mountains.

Vein carbonates within the Proterozoic sequences of the Rocky Mountains have $\delta^{18}O$ values spanning a range from 12.0 to 16.7‰, with a mean value of 14.0±1.4‰ (n=10). Two Miette limestones have an average $\delta^{18}O$ of 14.4‰. This indicates depletion in ^{18}O relative to typical $\delta^{18}O$ values of Proterozoic limestones, which range from 20 to 23‰ (Veizer, 1983).

Compared to the veins hosted by Precambrian rocks, the vein carbonates hosted by Paleozoic sequences are characterized by higher $\delta^{18}O$ values. Exhibiting a range in $\delta^{18}O$ from 12.7 to 21.3‰, the average $\delta^{18}O$ value for these carbonates is 18.0±2.4‰ (n=11). A depletion in $\delta^{18}O$ is noted in the replacement minerals that were formed from preorogenic fluids. Epigenetic dolomites and dolomitic breccias from the Pb-Zn mineralization at the Monarch and Kicking Horse mines within the Paleozoic units range in $\delta^{18}O$ from 13 to 18‰ (Nesbitt *et al.*, 1993). Cambrian limestones have $\delta^{18}O$ values from 17 to 22‰ (Nesbitt and Muehlenbachs, 1993), revealing that both the limestones and replacement minerals are slightly depleted in ^{18}O relative to typical Paleozoic limestones $\delta^{18}O$ values, which range from 20-23‰ (Veizer, 1983).

Figure 3 maps the $\delta^{18}O$ values of vein carbonates from the Omineca belt to the Fraser Fault region. Within the Omineca belt, $\delta^{18}O$ values of vein

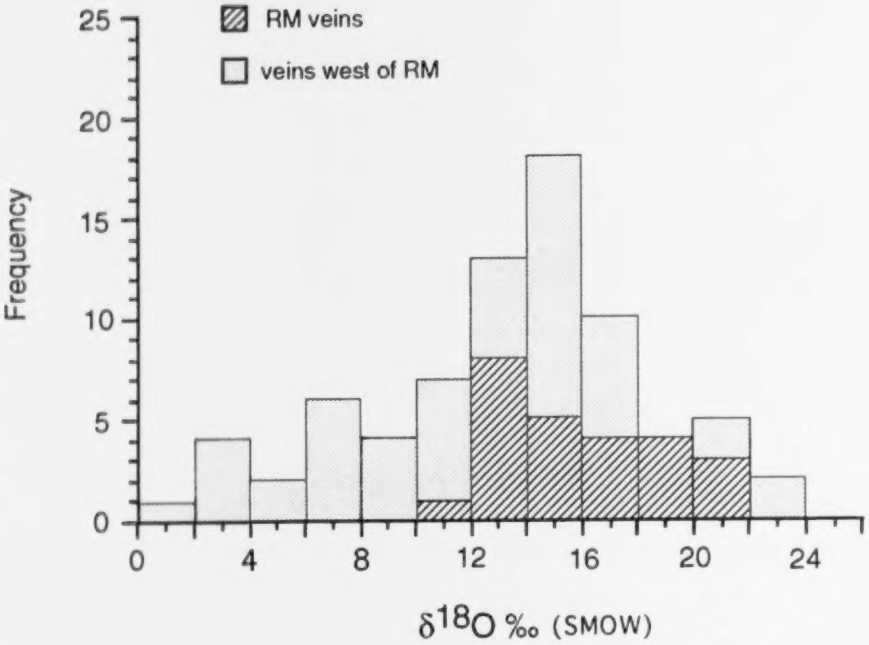
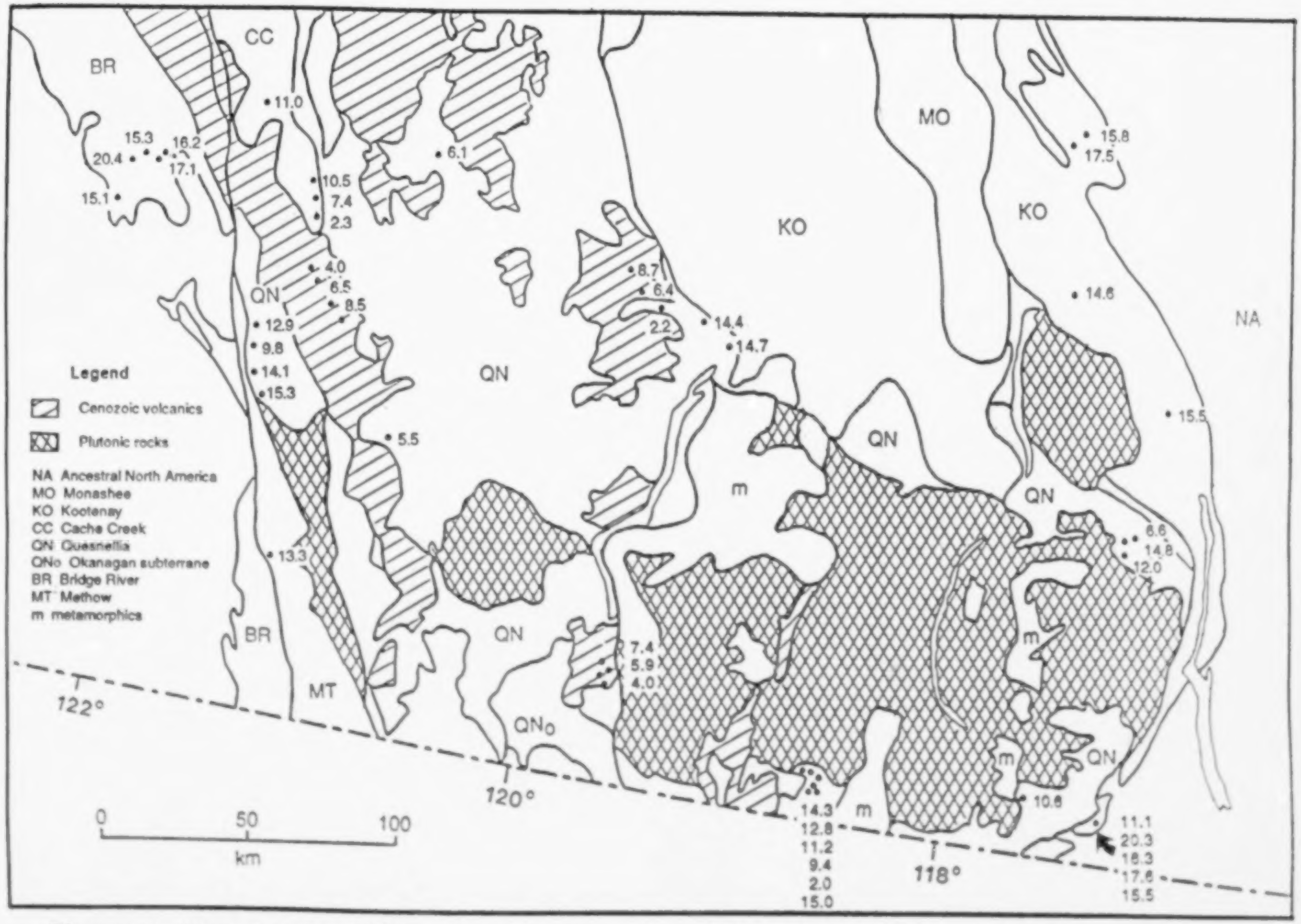


Figure 2 Histogram showing the $\delta^{18}O$ values for vein carbonate of the Rocky Mountain belt westward to the Fraser Fault region.


BR
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4.0
6.5
8.5
12.9
9.8
14.1
15.3
5.5
13.3
8.7
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Cenozoic volcanics
Plutonic rocks
NA Ancestral North America
MO Monashee
KO Kootenay
CC Cache Creek
QN Quesnellia
QNo Okanagan subterrane
BR Bridge River
MT Methow
m metamorphics

Figure 3 Map showing $\delta^{18}O$ values of vein carbonate from the Omineca belt to the Fraser Fault region. Modified after Wheeler *et al.* (1991).

carbonate are highly variable, having a range from 1.4 to 23.6‰. In the Cariboo district, vein calcites hosted by limestones have $\delta^{18}O$ values of 17.4 to 23.6‰, with the exception of one sample having a value of 1.4‰. Veins from the Slide Mountain Group have considerably lower $\delta^{18}O$ values than the Cariboo samples to the west. Two calcite veins yielded values of 12.6 and 13.3‰. Rocks hosting these veins are pillow basalts and argillaceous limestones, respectively.

In the Kootenay Arc to the south, $\delta^{18}O$ values of regional vein calcites and dolomites hosted by Paleozoic metasedimentary rocks span a range from 14.6 to 17.5‰. Also located in this region are mineralized vein calcites from the Sheep Creek mesothermal gold deposit. Vein carbonates from this deposit have $\delta^{18}O$ values that range from 11.1 to 20.3‰, and show greater heterogeneity than the regional veins. Cambrian limestones analysed of the Sheep Creek district have a mean $\delta^{18}O$ value of 20.6 ± 1.6‰ (n=4) (Hardy, 1992). It is evident that the mineralized veins show a depletion in ^{18}O relative to the limestones. North of the Nelson batholith, veins hosted by shales of the Slocan Group vary from 6.6 to 14.8‰, which are among the lowest $\delta^{18}O$ values observed in the Cordillera. A limestone sample from this region has a $\delta^{18}O$ value of 8.0‰, which is very low when compared to typical Paleozoic limestones ($\delta^{18}O$ =20-23‰, Veizer, 1983).

The lowest $\delta^{18}O$ values in the southern Canadian Cordillera occur in the Intermontane belt. Calcite veins from the volcanic rocks of the Nicola Group range from 5.5 to 14.7‰. Near the eastern boundary of the Intermontane belt, vein carbonates from Tertiary volcanics have $\delta^{18}O$ values from 4.0 to 8.7‰. At the western edge of the Intermontane belt near the Fraser Fault region, vein calcites situated within the Spences Bridge volcanics also have correspondingly low $\delta^{18}O$ values that range from 4 to 8‰.

In the Fraser Fault region, vein carbonates to the west of the Fraser fault system (Bridge River Group) have a mean $\delta^{18}O$ value of 16.8 ±2.1‰ (n=5). On the eastern side, vein carbonates of the Ladner Group and the Jackass Mountain Group have a mean $\delta^{18}O$ value of 13.1±2.0‰ (n=5).

C. Carbon Isotope Data

Figure 4 shows the range of $\delta^{13}C$ values obtained for vein carbonates across the Cordillera. Vein carbonates span a range of $\delta^{13}C$ values between -14 and +2‰. This reflects the overall heterogeneity of carbon isotopic compositions existing in the Rocky Mountains and in the Cordillera as a whole.

The lowest $\delta^{13}C$ values obtained in the entire southern Cordillera occur in the vein carbonates of the Proterozoic Miette Group in the Rocky Mountains, with a range from -7.2 to -13.2‰. Since typical organic carbon has $\delta^{13}C <$ -20‰ (Ohmoto and Rye, 1979), these low values indicate a component of organic carbon in the vein-forming fluid. The probable origin of carbon is the argillaceous units of the Miette Group. To the south near Lake Louise, one vein from the Miette group has a value of -2.7‰. This is a reflection of the close proximity of the vein to the Paleozoic carbonate strata in this region (Nesbitt *et al.*, 1993).

$\delta^{13}C$ values of -8.3 and -7.5‰ were obtained for two samples of limestone in the Miette clastic assemblages. Proterozoic limestones have typical $\delta^{13}C$ values of 0±2‰ (Ohmoto, 1986), indicating that these limestones have become depleted in $\delta^{13}C$ relative to unaltered limestones.

Vein carbonate and epigenetic dolomites from the Paleozoic sequences are less variable and less depleted in ^{13}C than the veins within the Proterozoic units. Vein carbonates east of the shale/carbonate facies transition have $\delta^{13}C$ values that fall between +1 to -2‰, with the exception of one sample having a value of -10.5‰. The carbonate rocks hosting the veins have a $\delta^{13}C$ ranging from +1 to -3‰. These values are typical for Cambrian marine limestones (Ohmoto and Rye, 1979). The source of carbon in these veins is consistent with derivation from the host carbonate rocks. In the shale sequences to the west, vein carbonates are also characterized by $\delta^{13}C$ values of -2 to +1‰ (Nesbitt *et al.*, 1993). Due to the organic content of shales, these values are higher than would be expected for carbonate veins hosted by shale sequences.

The geographic variation of $\delta^{13}C$ values for carbonate veins in the Omineca and Intermontane belts and the Fraser Fault region are illustrated in Figure 5. Within the Omineca belt, vein carbonates span a range from -9.4 to -0.1‰. Calcite veins in the Cariboo district have $\delta^{13}C$ values from -3.4 to -0.1‰, reflecting a contribution of ^{13}C from the host argillaceous limestones. Veins hosted by basalts and limestones of the Slide Mountain Group have $\delta^{13}C$

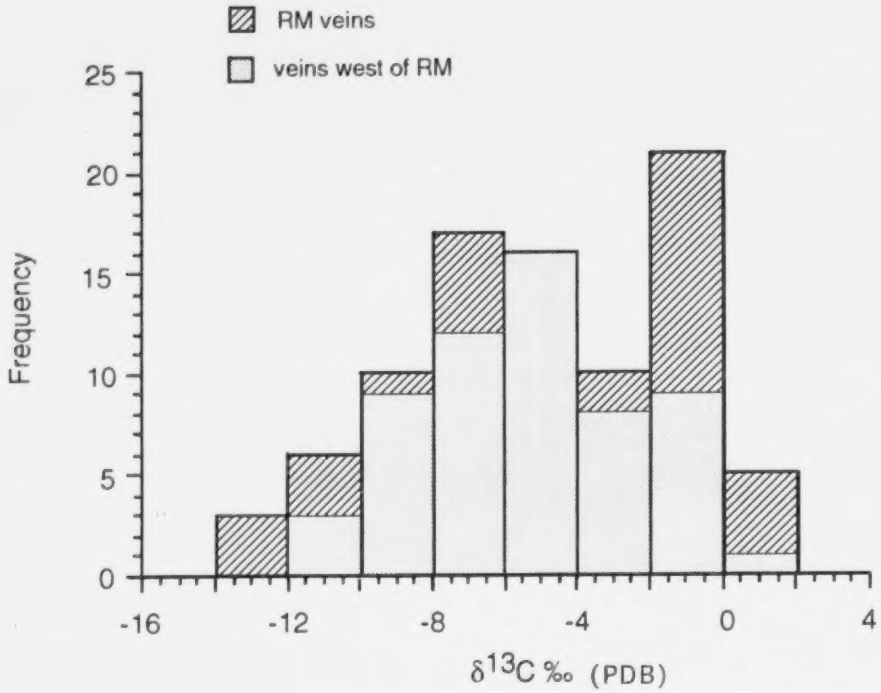
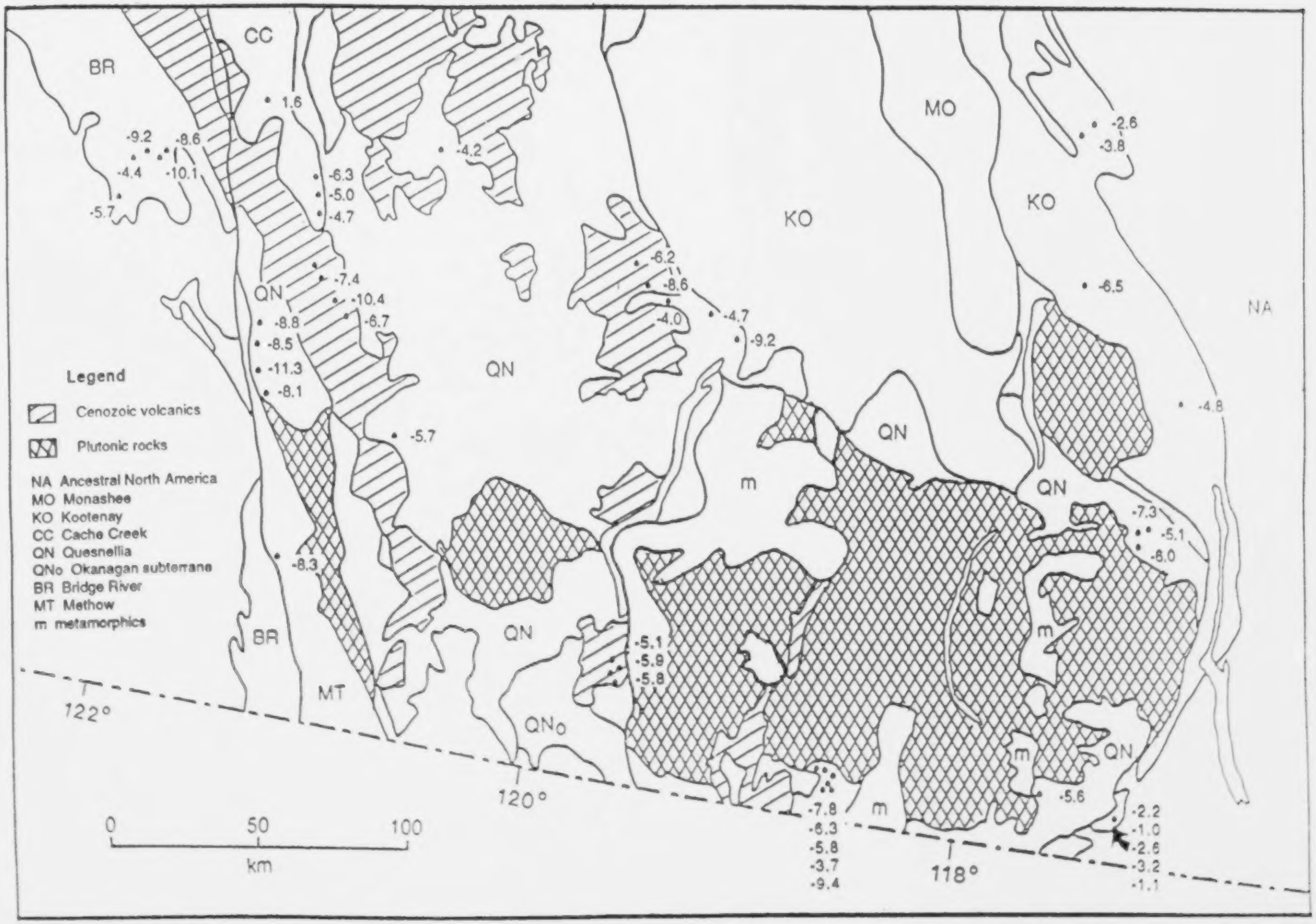


Figure 4 Histogram showing the $\delta^{13}C$ values for vein carbonate of the Rocky Mountain belt and westward to the Fraser Fault region.



Legend
Cenozoic volcanics
Plutonic rocks
NA Ancestral North America
MO Monashee
KO Kootenay
CC Cache Creek
QN Quesnellia
QNo Okanagan subterrane
BR Bridge River
MT Methow
m metamorphics
BR
CC
MO
KO
QN
NA
MT
QNo
m
122°
120°
118°
0
50
100
km
-9.2
-8.6
-4.4
-10.1
-5.7
1.6
-6.3
-5.0
-4.7
-4.2
-7.4
-10.4
-6.7
-8.8
-8.5
-11.3
-8.1
-5.7
-8.3
-6.2
-8.6
-4.0
-4.7
-9.2
-5.1
-5.9
-5.8
-7.8
-6.3
-5.8
-3.7
-9.4
-2.6
-3.8
-6.5
-4.8
-7.3
-5.1
-6.0
-5.6
-2.2
-1.0
-2.6
-3.2
-1.1

Figure 5 Map showing $\delta^{13}C$ values of vein carbonate from the Omineca belt to the Fraser Fault region. Modified after Wheeler et al. (1991).

values of -7.4 and -2.1‰, respectively. Further south, calcite veins in the Slocan Group to the north of the Nelson batholith exhibit a mean $\delta^{13}C$ value of -6.2 ± 0.9‰ (n=3). This is similar to the values obtained by Beaudoin *et al.* (1992) of -7.0 ± 0.5‰ for siderites in this region. $\delta^{13}C$ values of the vein carbonates of the Rossland Group and the Greenwood district in the Quesnellia terrane vary from -3.7 to -9.4‰. These veins, having a mean values of -6.4 ± 2.0‰, are slightly more depleted in ^{13}C than veins from the Kootenay Arc, which average -3.1 ± 1.8‰.

Vein carbonates hosted by volcanic and sedimentary rocks from the Intermontane belt show a scatter in $\delta^{13}C$ values from -9.2 to +1.6‰. The more depleted values occur in the volcanic-hosted vein calcites of the Nicola Group and Tertiary rocks, and range between -9 and -5‰. Carbon isotopic values of typical igneous rocks are generally -5 ± 2‰ (Ohmoto, 1986) which suggests that these samples have inherited the magmatic signature of the host rocks. These values, however, are not unique to magmatic rocks. The average $\delta^{13}C$ composition of sedimentary and metamorphic rocks is also -5 ± 2‰ (Ohmoto and Rye, 1979). Consequently, the origin of carbon in these rocks can not be determined. One sample from the Cache Creek Group yielded a $\delta^{13}C$ value of +1.6‰ (Nesbitt *et al.*, 1993). This enriched $\delta^{13}C$ value reflects the prevalence of limestones in this region.

The Fraser Fault region contains among the lowest $\delta^{13}C$ values in vein carbonate observed in the Cordillera. Hosting the veins are metasedimentary rocks of the Bridge River Group and Jackass Mountain Group. With the exception of one sample ($\delta^{13}C$ = -4.4‰), $\delta^{13}C$ values are generally < -6‰ and as low as -11.3‰. These low values indicate a component of reduced carbon from either organic-rich sediments or graphite in metamorphic rocks.

D. Interpretation of Stable Isotope Data

Zones of enrichment and depletion of $\delta^{18}O$ values in carbonates are evident across the southern Canadian Cordillera. The highest values occur in the Paleozoic sequences in the Rocky Mountains. Moderately enriched $\delta^{18}O$ values from 14-16‰ occur in the vein carbonates within the Proterozoic rocks of the Rockies, the Cariboo district in the Omineca belt, and the Fraser Fault region. Vein carbonates in the Intermontane belt and in parts of the Omineca belt, such as the Slocan region, have the lowest $\delta^{18}O$ values.

The isotopic distribution of $\delta^{18}O$ of vein carbonates roughly parallels the trend observed in $\delta^{18}O$ in quartz veins obtained by Nesbitt *et al.* (1993). However, the $\delta^{18}O$ values are more depleted than those obtained from quartz veins by 1-2‰. This is due to the fractionation of oxygen between quartz and calcite. In equilibrium conditions, quartz is enriched in $\delta^{18}O$ by 1-2‰, for temperatures around 100-200°C. In spite of this fact, some regional differences in $\delta^{18}O$ between the carbonate values and the quartz values obtained by Nesbitt *et al.* (1993) are apparent. In the central part of the southern Cordillera, Nesbitt *et al.* (1993) obtained low $\delta^{18}O$ values in locations proximal to extensional faulting. In contrast, this study obtained low $\delta^{18}O$ values throughout the Intermontane belt. The lack of correlation may be due to the fact that coexisting quartz and calcite were formed from different fluids and thus represent different generations of veins. Certain veins consist solely of calcite or quartz, presenting a greater likelihood that the veins are of different ages or formed from different fluids.

Across the southern Cordillera, $\delta^{13}C$ values are consistent with derivation from host rocks. As a result, low $\delta^{13}C$ values are noted in the clastic rocks of the Proterozoic sequences and in the volcanic rocks of the Fraser Fault region. High $\delta^{13}C$ values typical of marine carbonates occur in the Paleozoic carbonate strata in the Rocky Mountains. The Omineca and the Intermontane belt have variable $\delta^{13}C$ values, reflecting an input from oxidized (carbonate) and reduced (organic derivation) carbon sources. The pattern obtained for vein carbonate $\delta^{18}C$ values across the southern Canadian Cordillera corresponds to the variations obtained by Nesbitt *et al.* (1993), but is less detailed due to a smaller sampling set. The observed regional variations of $\delta^{13}C$ in vein carbonates seems to be generally controlled by the $\delta^{13}C$ values in the host rocks.

V. STRONTIUM ISOTOPE GEOCHEMISTRY

A. Introduction

Although hydrothermal fluid regimes in the Canadian Cordillera have been investigated using stable isotopes ($\delta^{18}O$, δD, $\delta^{13}C$), and fluid inclusions (Nesbitt and Muehlenbachs, 1989a; Margaritz and Taylor, 1986), the fluid regimes have yet to be characterized using strontium isotopic compositions. In this study Sr isotopes are used as tracers to determine the patterns of fluid flow within the Canadian Cordillera at a variety of scales: hand sample, outcrop and regional. Furthermore, they are used to provide information on the extent of water-rock interaction between fluids and the rock units. The possibility of distinguishing veins hosting mineralization from regionally barren veins through the use of Sr isotopic compositions has been investigated.

B. Homogeneity of Vein Strontium

It has been shown that isotopic homogeneity in stable isotopes exists within individual veins for distances up to hundreds of meters (Nesbitt *et al.*, 1989). However, the fact that Sr is a solute and not a solvent as is the case for O and H prevents us from making the same assumption for Sr behaviour in crustal fluids. It is important to determine whether individual veins are homogeneous or heterogeneous in Sr because the question may bear on the nature and detail of the conclusions that can ultimately be drawn from this database. Specifically, if the variation in the Sr isotopic composition within a vein is as large as the variability between vein systems, then it will not be possible to distinguish between different fluid systems. Accordingly, different parts of individual veins have been analysed in order to determine the amount of Sr isotopic variation present within one vein. The results for four different veins are shown on Table 3. The sample spacing within the veins was on the order of several meters.

Sample AK91-16 is a vein hosted by phyllites of the Jackass Mountain Group in the Fraser Fault region. Two analyses from different portions of the vein yield $^{87}Sr/^{86}Sr$ ratios of 0.70378 ±6 and 0.70377 ±5, and the analyses are within analytical error (ie. the instrumental variability in sample runs). The largest difference in Sr ratios within a vein is 0.0055, occurring in a vein from the Paleozoic shale sequences of the Rocky Mountain belt (AK91-1). A variation in $^{87}Sr/^{86}Sr$ of 0.0032 was observed for a vein from the Sheep Creek mesothermal gold deposit (Vsc 357).

Table 3 Comparison of strontium ratios within individual veins.

Sample	$^{87}Sr/^{86}Sr$
AK91-1	0.72022 ±7
AK91-1 duplicate	0.72000 ±9
AK91-1b	0.71468 ±5
AK91-4	0.71492 ±5
AK91-4b	0.71454 ±15
AK91-16	0.70378 ±6
AK91-16b	0.70377 ±5
Vsc 357	0.71155 ±3
Vsc 357b	0.71472 ±4

The geochemical variations found in these samples suggest that the carbonate veins were formed by hydrothermal fluids that had chemically evolved through time. The fluids may have migrated along different pathways and leached rocks units that were isotopically different from the previous package of rocks. This may have produced isotopic zoning within the vein.

It is important to note that the variation within individual veins is smaller than the variation among samples from each geological setting. Hence, distinctions in Sr compositions between vein systems from tectonically different regions can be made.

Strontium isotopic ratios and strontium concentrations for regional vein carbonates across the southern Canadian Cordillera are presented in Table 4. In order to compare the strontium ratios of veins to those of host rocks, the timing of the formation of hydrothermal carbonate (which in certain cases corresponds to the timing of mineralization) must be known or estimated. Using this information, $^{87}Sr/^{86}Sr$ values of the host rocks were recalculated to their approximate isotopic composition at the time of vein formation. The

Table 4 Strontium isotopic data for regional carbonate veins

Unit and Sample[1]	Mineral	$^{87}Sr/^{86}Sr$	$\pm 2\sigma$ $(\bullet 10^{-5})$	Sr conc (ppm)	Host Rock
ROCKY MOUNTAIN BELT					
Preorogenic Fluid Event					
RB 624	dolomite	0.70968	13	-	dolostone
RB 625		0.70922	14	25	dolostone
RB 659		0.70961	7	-	limestone
RB 695		0.71012	6	213	limestone
RB 706		0.70990	5	1798	limestone
RB 732	dol. breccia	0.71054	8	27	
RB 733	dol. breccia	0.71092	9	80	
RB 810	dolomite	0.71191	5	-	dolostone
RB 824	magnesite	0.70996	8	-	magnesite
RB 825	magnesite	0.71024	21		magnesite
Syn- to Postorogenic Fluid Event					
Miette Group					
RB 562		0.75603	12	-	slate
RB 563	calcite	0.74623	19	166	slate
RB 567		0.77831	15	-	slate
RB 569	calcite	0.73869	7	691	
RB 570	calcite	0.75192	4	-	quartzite
RB 573	calcite	0.77414	5	653	shale
RB 576	calcite	0.77150	3	-	
RB 604	calcite	0.75395	4	-	phyllite
RB 636	ankerite	0.76505	1	39	slate
RB 639	calcite	0.75702	10	1593	
RB 641	calcite	0.73092	3	1154	
RB 671	calcite	0.74028	7	-	
RB 754		0.73349	5	408	limestone
RB 755		0.73548	10	444	limestone
Paleozoic Carbonate Sequences					
RB 678	calcite	0.70922	4	890	limestone
RB 679	calcite	0.70931	10	-	limestone
RB 682	calcite	0.70910	2	-	
RB 710		0.70908	3	372	limestone
Paleozoic Clastic Sequences					
RB 257	calcite	0.71319	9	-	shale
RB 472b	calcite	0.71419	19	-	shale
RB 477	calcite	0.71019	9	-	quartzite
RB 651	calcite	0.71855	3	-	phyllite
RB 662	calcite	0.70943	4	6151	slate
RB 707		0.71882	5	-	shale
AK91-1	calcite	0.72022	6	796	phyllite
AK91-1b	calcite	0.71468	5	-	phyllite
AK91-2	calcite	0.71239	4	898	mudstone
AK91-3	calcite	0.71676	4	1854	mudstone

Unit and Sample	Mineral	$^{87}Sr/^{86}Sr$	±2σ $(*10^{-5})$	Sr conc (ppm)	Host Rock
OMINECA BELT					
Cariboo District					
C45	calcite	0.70964	13	-	marble
C46	calcite	0.70890	4	-	marble
C47a		0.70880	4	-	marble
C48a	calcite	0.70882	4	-	limestone
Slide Mountain Group					
SM2	calcite	0.70617	9	-	basalt
SM3b	calcite	0.71339	5	-	limestone
Kootenay Arc					
AK91-4	Fe calcite	0.71492	5	1051	phyllite
AK91-4b	Fe calcite	0.71454	15	-	phyllite
AK91-4a		0.71672	31	-	phyllite
AK91-5	Fe calcite	0.71641	3	698	phyllite
AK91-5a		0.71772	22	-	phyllite
AK90-7	Fe calcite	0.72347	5	111	slate
AK90-8	calcite	0.73838	5	700	phyllite
AK90-9	Fe dolomite	0.71340	10	618	phyllite
Slocan Group					
AK91-27	calcite	0.70559	4	836	limestone
AK91-27a		0.70606	4	751	limestone
AK91-28	calcite	0.71329	10	1567	mudstone
AK91-29	dolomite	0.71022	1	1219	limestone
AK91-30	calcite	0.70473	7	985	mudstone
Rossland Group					
AK90-13	calcite	0.70612	7	1132	siltstone
AK90-14	calcite	0.70592	8	1127	siltstone
INTERMONTANE BELT					
Nicola Group[2]					
AK91-6	calcite	0.70460	4	1693	slate
AK91-6a		0.70513	3	-	slate
AK91-7	calcite	0.70395	3	1010	limestone
AK91-7a		0.70400	2	1655	limestone
AK91-8	ankerite	0.70449	4	-	shale
RB 340	dolomite	0.70431	4	-	
AK90-38	calcite	0.70382		-	volcanic
Late Paleozoic Sequence					
AK91-9	Fe calcite	0.70665	26	37	limestone
AK91-9a		0.70651	15	-	limestone
Tertiary Volcanics					
AK91-10	calcite	0.70649	7	37	volcanic
AK91-11	calcite	0.70530	17	246	volcanic
EE92-8	calcite	0.70698	3	-	volcanic
EE92-10	calcite	0.70645	30	-	volcanic
EE92-19	calcite	0.70533	3	-	volcanic
EE92-4	calcite	0.70524	4	-	volcanic

Unit and Sample	Mineral	$^{87}Sr/^{86}Sr$	$\pm 2\sigma$ $(*10^{-5})$		Host Rock
EE92-12	calcite	0.70695	4	-	volcanic
EE92-13	calcite	0.70654	3	-	volcanic
EE92-16	calcite	0.70715	8	-	volcanic
Cache Creek Group					
RB 358	calcite	0.70611	3	-	limestone
AK91-24	calcite	0.70572	2	236	greenschist
AK91-25	calcite	0.70569	8	160	greenschist
AK91-26	calcite	0.70566	5	454	greenschist
Spences Bridge Group					
AK91-20	calcite	0.70382	3	207	volcanic
AK91-21	calcite	0.70538	16	70	volcanic
AK91-22	calcite	0.70349	5	292	volcanic
AK91-22a		0.70382	17	-	volcanic
AK91-23	calcite	0.70360	3	156	volcanic
Fraser Fault Region					
Jackass Mtn Group					
AK91-16	Fe calcite	0.70378	6	1848	phyllite
AK91-16b	Fe calcite	0.70377	5	-	phyllite
AK91-16a		0.70351	22	-	phyllite
AK91-17	calcite	0.70388	7	1331	mudstone
AK91-18	calcite	0.70531	16	169	mudstone
AK91-19	calcite	0.70385	4	1243	shale
Ladner Group					
AK90-36	calcite	0.70455	7	340	mudstone
Bridge River Group					
AK91-12	calcite	0.70442	6	1043	mudstone
AK91-13	calcite	0.70400	5	1132	schist
AK91-14	dolomite	0.70669	5	1127	schist
AK91-15	calcite	0.70452	6	102	schist
RB 381	calcite	0.70415	9	-	schist

Notes:

[1] Sample in bold type indicates analysis of host rock.

[2] The area of sampling covers both the Omineca Belt and the Intermontane Belt.

remainder of this chapter is devoted to detailed descriptions and results of strontium isotopic studies of vein carbonates and host rocks from the different geological domains of the Canadian Cordillera.

C. Rocky Mountain Belt

Veins in the Rocky Mountain belt were sampled from the Proterozoic Miette Group and from clastic and carbonate sequences of Paleozoic age between the Bow and the Athabasca rivers. Sample locations are shown on Figures 6 and 7. The mean and range of $^{87}Sr/^{86}Sr$ ratios obtained for vein carbonates, secondary minerals and host rocks of the Rocky Mountain belt are presented in Figure 8.

Preorogenic Fluid Event

The majority of minerals and replacement zones formed from preorogenic fluids were sampled from the mid-Cambrian Cathedral Formation, a unit comprised of platformal limestones and their dolomitized equivalents. The Mount Brussilof magnesite deposit, and various Pb-Zn deposits such as the Monarch mine and Kicking Horse mine, are situated within this formation. Epigenetic dolomites are found within the strata in addition to other Paleozoic carbonate units. To the west is a transition to deep water shale sequences of the Chancellor Formation.

One Cambrian limestone from the Cathedral Formation (RB710) has a Sr isotopic ratio of 0.7091, which is typical of unaltered limestones of mid-Cambrian age (Burke *et al.*, 1982). However, several limestones from this formation show elevated Sr ratios, ranging from 0.7096 to 0.7101. Furthermore, samples from the magnesite deposit (RB 824, 825) average 0.7101 ± 0.0002. Dolomitic gangue from the Pb-Zn occurrence at the Kicking Horse mine (RB 732, 733) have ratios of 0.7105 and 0.7109. Coarse, sparry dolomites range from 0.7092 to 0.7119. These values are all slightly higher than the Sr ratios typical of Cambrian limestone (0.7089-0.7093, Burke *et al.*, 1982). This suggests that external fluids have reset the Sr signatures of the Cambrian limestones and may also be responsible for the formation of the secondary carbonates within the Paleozoic limestone sequences.

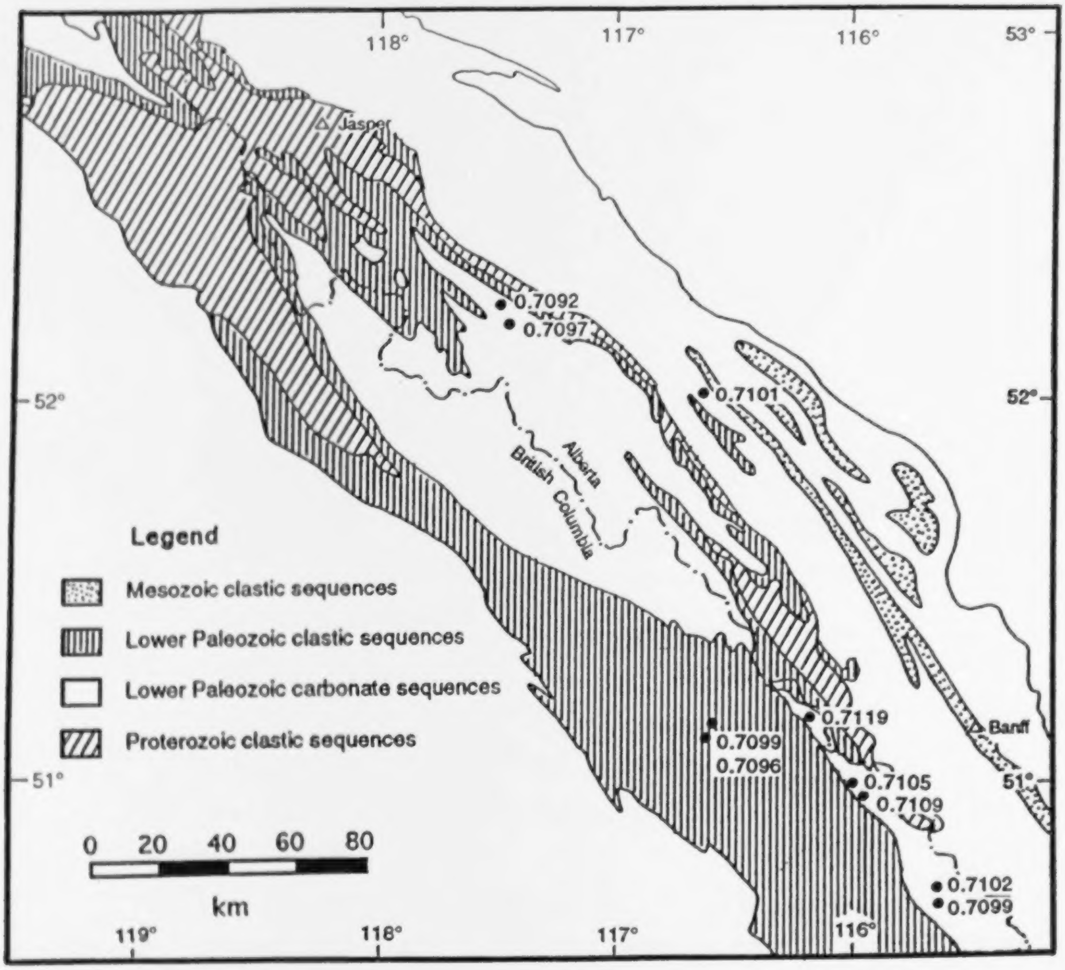
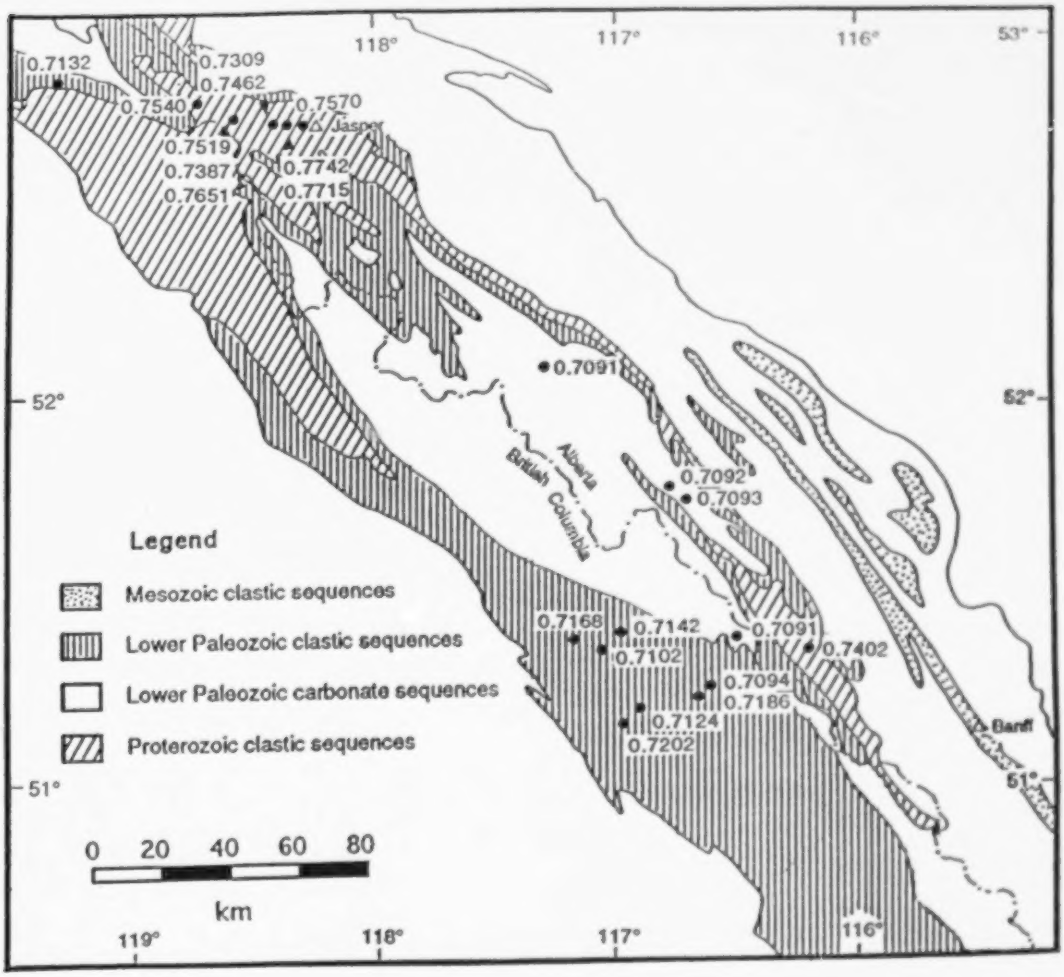

118°
117°
116°
53°
Jasper
0.7092
0.7097
0.7101
52°
52°
Alberta
British Columbia
Legend
Mesozoic clastic sequences
Lower Paleozoic clastic sequences
Lower Paleozoic carbonate sequences
Proterozoic clastic sequences
0.7119
Banff
0.7099
0.7096
51°
51°
0.7105
0.7109
0 20 40 60 80
km
0.7102
0.7099
119°
118°
117°
116°

Figure 6 Map showing the $^{87}Sr/^{86}Sr$ values of carbonate rocks of the Preorogenic Fluid Event in the Rocky Mountain belt (simplified after Wheeler and McFeely, 1987).



118°
117°
116°
53°
0.7132
0.7309
0.7462
0.7540
0.7570
Jasper
0.7519
0.7387
0.7651
0.7742
0.7715
0.7091
52°
52°
Alberta
British Columbia
0.7092
0.7093
Legend
Mesozoic clastic sequences
Lower Paleozoic clastic sequences
Lower Paleozoic carbonate sequences
Proterozoic clastic sequences
0.7168
0.7142
0.7102
0.7091
0.7402
0.7094
0.7186
0.7124
0.7202
Banff
51°
51°
0
20
40
60
80
km
119°
118°
117°
116°

Figure 7 Map showing the $^{87}Sr/^{86}Sr$ values of vein carbonates of the Syn- to postorogenic Fluid Event in the Rocky Mountain belt (simplified after Wheeler and McFeely, 1987).

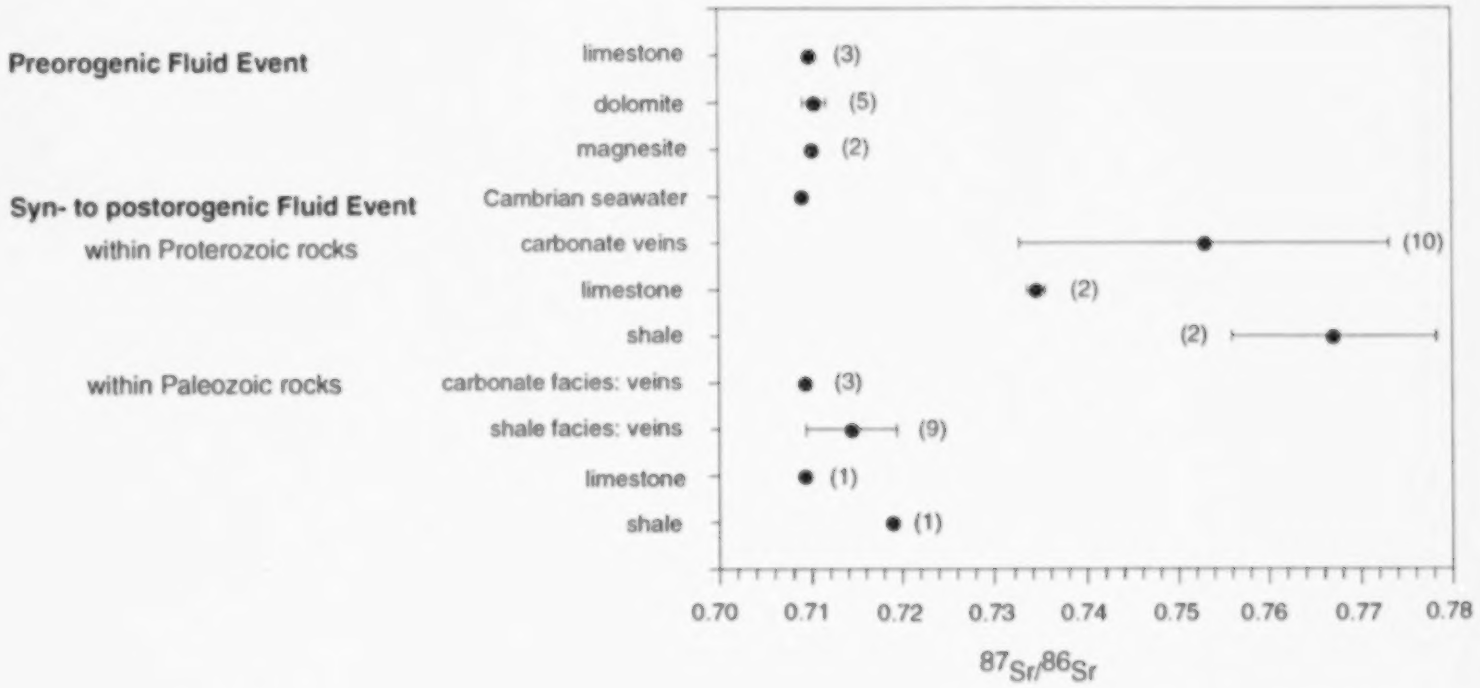


Figure 8 Strontium isotope ratios of vein carbonates and host rocks from the Rocky Mountains, showing the mean and range. Number in brackets refers to the number of samples.

Evidence from oxygen and fluid inclusion data suggest that preorogenic fluids caused widespread chemical and isotopic alteration within the Paleozoic limestones sequences and were responsible for the formation of epigenetic dolomites, magnesite, talc and Pb-Zn mineralizations (Nesbitt and Muehlenbachs, 1993). Fluid inclusion data indicate that these fluids were saline and reached a temperature of 150 ± 25°C (Nesbitt and Muehlenbachs, 1993). West to east variations in both the fluid $\delta^{18}0$ values and the intensity of dolomitization indicate that the observed alteration is the result of the movement of fluids that originated in the shales and moved eastwards through the carbonate sequences (Nesbitt *et al.*, 1993). A fluid originating in the shale sequences would also possess the radiogenic Sr values that are observed in the altered limestones and secondary minerals to the east of the shale/limestone facies transition.

Syn- to Postorogenic Fluid Event

Vein carbonates in Proterozoic rocks

Within the Miette Group, vein carbonates have $^{87}Sr/^{86}Sr$ values spanning a range from 0.7309 to 0.7715, averaging 0.7530 ± 0.0144 (n=10). These are the highest values obtained for any vein system analysed in the southern Cordillera. The veins also exhibit extremely variable strontium ratios (Figure 8).

The Proterozoic age rocks hosting the vein carbonates consist mainly of sandstone, shale, conglomerate and minor carbonate (Gabrielse and Campbell, 1991). Two shales hosting the veins have measured $^{87}Sr/^{86}Sr$ values of 0.7560 and 0.7783. Estimating that the time of vein formation was early Tertiary (approximate age for syn- to postorogenic fluids), the initial Sr ratios are 0.7532 and 0.7730. These values indicate that the shales have likely contributed strontium to the fluids which formed the carbonate veins. Consequently, it is reasonable to suggest that the shales (and other clastic sedimentary rocks of the Miette Group) are the probable source of radiogenic Sr noted in the vein carbonates.

Two limestones within the Miette Group have $^{87}Sr/^{86}Sr$ values of 0.7335 and 0.7355. These values are high relative to unaltered limestones of the late Proterozoic, which have $^{87}Sr/^{86}Sr$ values of 0.707-0.709 (Asmeron *et al.*, 1991; Veizer *et al.*, 1983). The highly radiogenic limestones have clearly been altered by external fluids. These fluids most probably equilibrated from the contiguous clastic rocks of the Miette Group.

Vein carbonates in Paleozoic rocks

Within the Paleozoic sequences, veins produced by syn- to postorogenic fluids occur both east and west of the shale/carbonate facies transition. To the east, $^{87}Sr/^{86}Sr$ values of vein carbonates in the mid-Cambrian limestones range from 0.7091 to 0.7093. One limestone (RB710) has a value of 0.7091, reflecting mid-Cambrian marine limestone compositions (0.7089-0.7093, Burke *et al.*, 1982).

To the west of the facies transition lies the Chancellor Formation, which consists of deep water shales and carbonaceous sediments (Stewart, 1991). Vein carbonates within the Chancellor Formation exhibit $^{87}Sr/^{86}Sr$ values which vary from 0.7124 to 0.7202. The vein carbonates show a progressive decrease in $^{87}Sr/^{86}Sr$ from the western part of the Chancellor Formation to the eastern part, reflecting a closer proximity to the platform carbonates.

A single shale sample from the Chancellor Formation yielded a value of 0.7188. Assuming that the age of the veins is Eocene, the $^{87}Sr/^{86}Sr$ ratio of the shale at the time of vein formation would have been 0.7184. This high value suggests that the shales of the Chancellor Formation may be a source of strontium in the vein.

To summarize, it is possible to distinguish two distinct fluid regimes in the Rockies on the basis of Sr isotopic composition of vein carbonates. Replacement minerals and altered host rocks from preorogenic fluids have $^{87}Sr/^{86}Sr$ ratios that range from 0.7092 to 0.7119. The values are slightly higher than the Sr values expected for vein rocks that had precipitated from seawater during the Paleozoic. Syn- to postorogenic fluids produced vein carbonates that have $^{87}Sr/^{86}Sr$ values consistent with derivation from the host rocks. Whereas preorogenic fluids appear to have chemically altered the host rocks (Nesbitt *et al.*, 1993), veins formed from syn- to postorogenic fluids have incorporated Sr isotopic compositions from the host rocks. Strontium isotopic signatures of vein carbonates that were formed from these later fluids are in good agreement with host rock isotopic compositions in both the Proterozoic and Paleozoic strata.

Vein carbonates that formed from syn- to postorogenic fluids can be further classified by the age and composition of their host rocks. Combining oxygen, carbon and strontium data, the veins hosted by the Proterozoic clastic sequences are distinguished from veins within the Paleozoic sequences, which consist of clastic and carbonate rocks. Figures 9 and 10 reveal two distinct populations of vein carbonates. In Figure 9, it is evident that the vein carbonates hosted by the Miette Group are more radiogenic and more depleted in ^{18}O than vein carbonates hosted by the Paleozoic sequences. Figure 10 illustrates that the veins hosted in Paleozoic rocks are lower in $^{87}Sr/^{86}Sr$ and depleted in ^{13}C than veins within the Miette Group.

D. Omineca Belt

In the Omineca belt, vein carbonates were sampled from the Cariboo district in the Barkerville subterrane, the Kootenay Arc in the Kootenay terrane, the Slide Mountain terrane and the Quesnellia terrane. Subdivided within the Quesnel terrane are veins hosted by the Slocan Group and the Rossland Group. The locations and Sr isotopic compositions of vein carbonates of vein carbonates of the Cariboo District, and the Slide Mountain terrane are shown in Figure 11. Figure 12 shows the Sr isotopic compositions of vein carbonates within the Omineca belt, the Intermontane belt and the Fraser Fault system. The variation in Sr isotopic compositions shown in Figure 13 is greatest in the Omineca belt, and in particular, within the Kootenay Arc. This variation decreases to the west in the Intermontane belt and the Fraser Fault region.

Slide Mountain Terrane

Rocks of the Slide Mountain terrane are predominantly volcanic rocks which include pillow basalts, gabbro and ultramafic rocks. Chert and pelitic assemblages are found in lesser abundance (Smith, 1986; Struik, 1988). The sequences, ranging in age from Mississippian to Permian, are interpreted to represent obducted oceanic crust. The rocks, Mississippian to Permian in age, are bounded by faults against the Barkerville subterrane (Struik, 1988). Assuming an age of 300 Ma for the basalts, Smith (1986) obtained a range of initial Sr ratios that range from 0.7025-0.7030. One volcanic-hosted vein

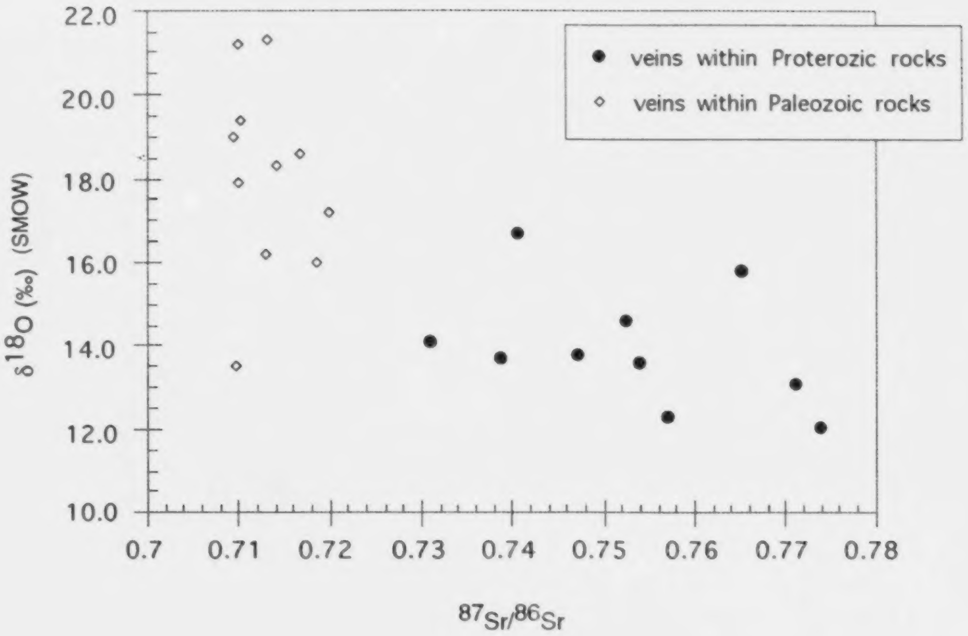


Figure 9 $^{87}Sr/^{86}Sr$ values versus $\delta^{18}O$ values, showing two distinct populations for veins in the Rocky Mountains.

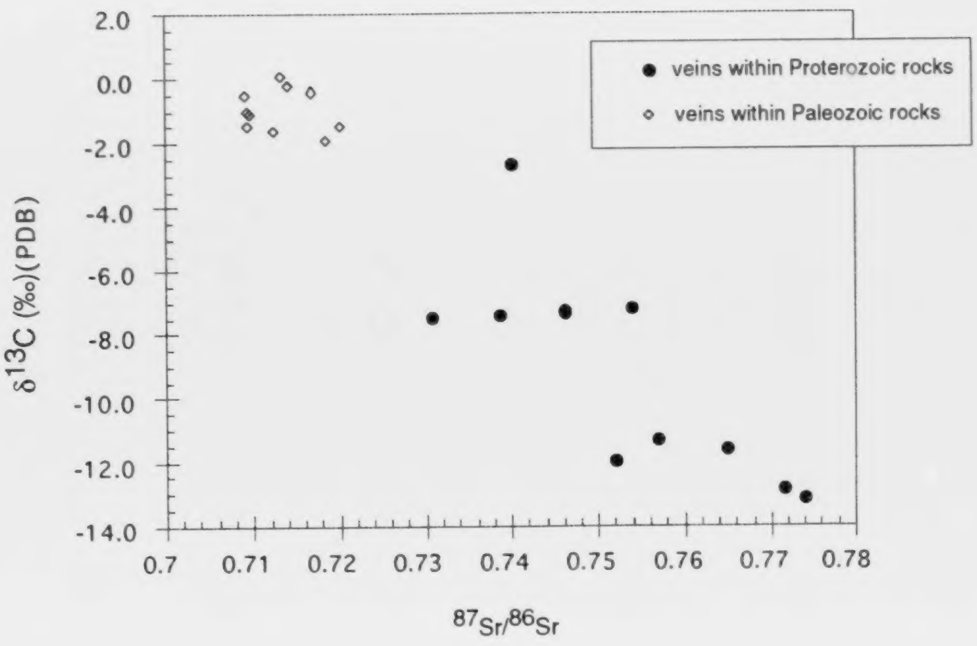


Figure 10 $^{87}Sr/^{86}Sr$ values versus $\delta^{13}C$ values, showing two distinct populations for veins in the Rocky Mountains.

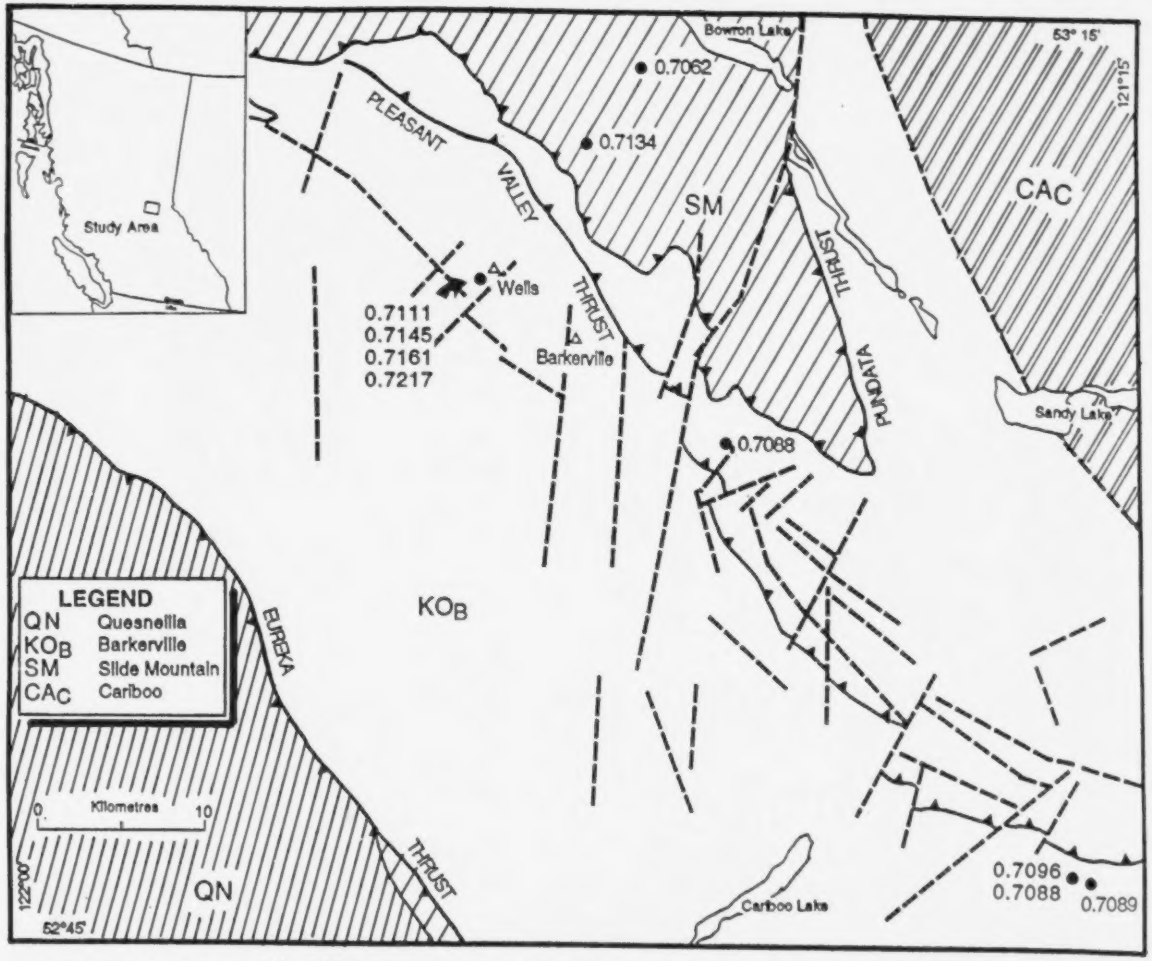

Bowron Lake
0.7062
0.7134
PLEASANT
VALLEY
THRUST
SM
THRUST
PUNDATA
CAC
53° 15'
121°15'
Study Area
Wells
0.7111
0.7145
0.7161
0.7217
Barkerville
0.7088
Sandy Lake
KOB
LEGEND
QN Quesnellia
KOB Barkerville
SM Slide Mountain
CAC Cariboo
EUREKA
THRUST
Kilometres
0
10
QN
122°00'
52°45'
Cariboo Lake
0.7096
0.7088
0.7089

Figure 11 Map of $^{87}Sr/^{86}Sr$ values of mineralized and regional vein carbonates of the Cariboo District and the Slide Mountain terrane. All contacts shown are faults. Modified after Struik, 1986

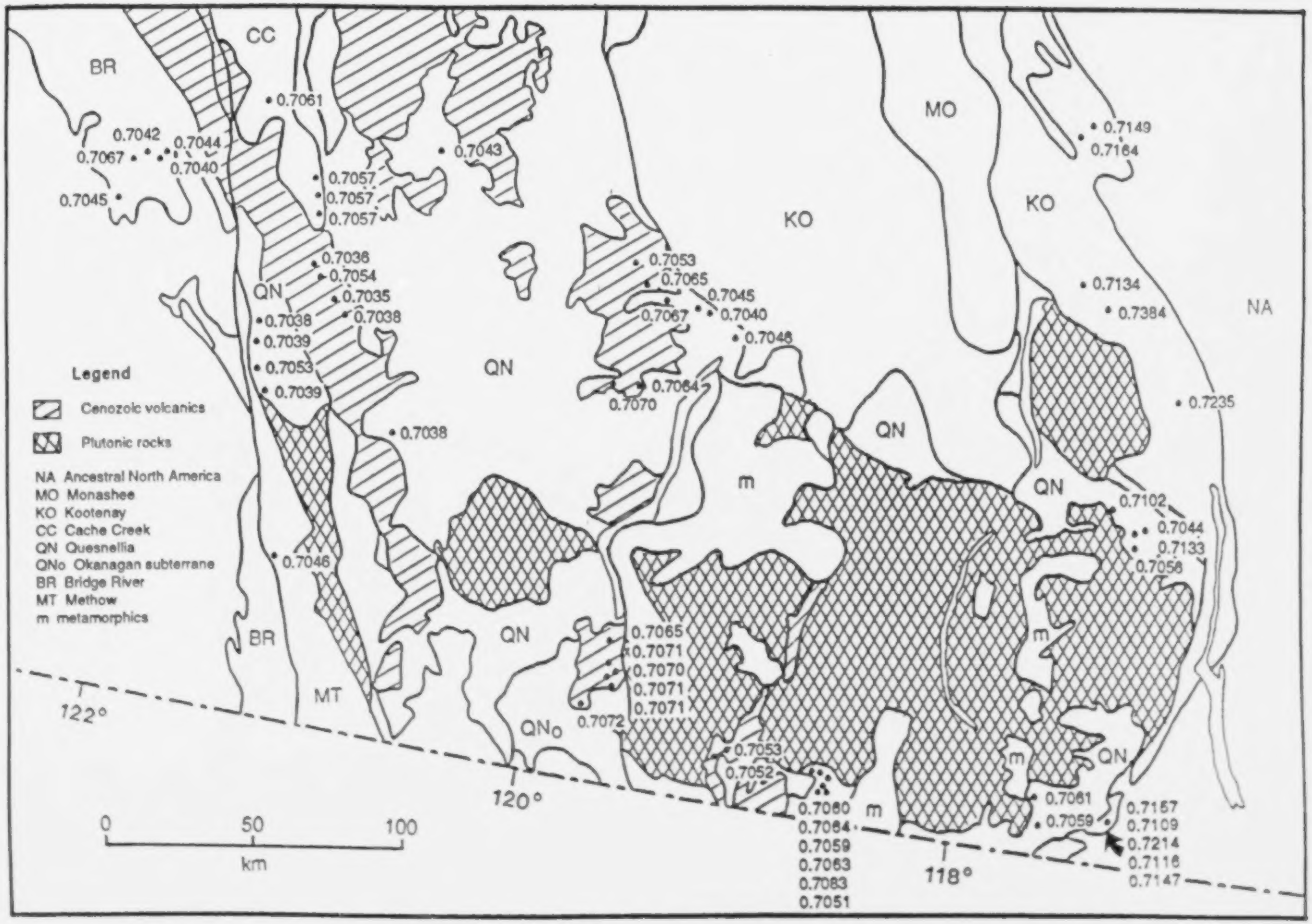

BR
CC
0.7061
0.7042
0.7044
0.7067
0.7040
0.7045
0.7043
0.7057
0.7057
0.7057
MO
0.7149
0.7164
KO
KO
0.7036
0.7054
0.7035
0.7038
QN
0.7038
0.7039
0.7053
0.7039
0.7053
0.7065
0.7045
0.7067
0.7040
0.7046
0.7134
0.7384
NA
Legend
Cenozoic volcanics
Plutonic rocks
NA Ancestral North America
MO Monashee
KO Kootenay
CC Cache Creek
QN Quesnellia
QNo Okanagan subterrane
BR Bridge River
MT Methow
m metamorphics
QN
0.7064
0.7070
0.7038
QN
0.7235
m
QN
0.7102
0.7044
0.7133
0.7056
0.7046
BR
QN
0.7065
0.7071
0.7070
0.7071
0.7071
m
0.7072
MT
122°
QNo
0.7053
0.7052
m
QN
120°
0.7060
0.7064
0.7059
0.7063
0.7083
0.7051
m
0.7061
0.7059
0.7157
0.7109
0.7214
0.7116
0.7147
118°
0
50
100
km

Figure 12 Map showing $^{87}Sr/^{86}Sr$ values of vein carbonate from the Omineca belt to the Fraser Fault region. Modified after Wheeler *et al.* (1991).

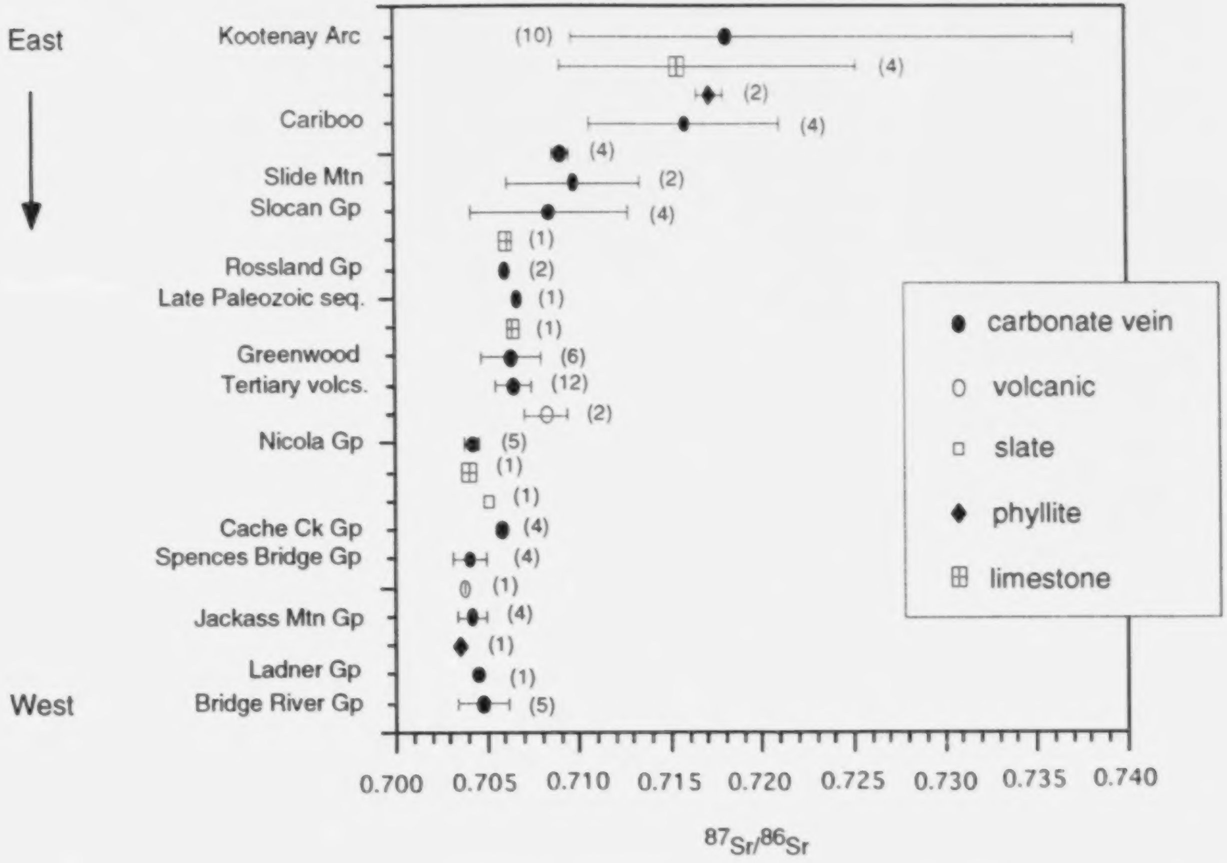


Figure 13 Strontium isotope ratios of vein carbonate and host rocks from the Omineca belt to the Fraser Fault region, showing the mean and the range. Number in brackets refers to number of samples.

calcite has a Sr value of 0.7062. One vein calcite hosted by limestones had a Sr value of 0.7134. Both values are higher than expected if the strontium in the vein calcites was derived from the host rocks.

Cariboo District

The Cariboo district is located within the Barkerville subterrane of the Kootenay terrane. The rocks are predominantly grit, quartzite, and pelitic strata, with minor limestones and volcaniclastic rocks. The rocks range in age from late Precambrian to Late Paleozoic. The rocks have been subjected to greenschist facies metamorphism in the Jurassic (Struik, 1988).

Barren calcite veins from the Cariboo district are characterized by $^{87}Sr/^{86}Sr$ values ranging from 0.7088 to 0.7096. A limestone yielded a value of 0.7088. Unaltered Late Proterozoic limestones have $^{87}Sr/^{86}Sr$ values ranging from 0.707-0.709 (Veizer *et al.*, 1983), indicating that the Sr isotopic values of the limestone have not been altered. Furthermore, the source of the strontium in the calcite veins is consistent with derivation from the limestones.

Strontium ratios of mineralized veins from the Cariboo gold district are in marked contrast to the Sr ratios of the barren veins. $^{87}Sr/^{86}Sr$ values varying from 0.7111 to 0.7217 were obtained for mineralized veins. This will be discussed further in the following chapter.

Kootenay Arc

The Kootenay Arc is a structural belt of generally high grade metamorphic rocks ranging in age from Late Proterozoic to Early Jurassic. It borders rocks from ancestral North America on the east (Purcell Anticlinorium) and rocks of accreted terranes on the west. In addition to being subjected to Mesozoic and Cenozoic plutonic activity, it has undergone both compressional and extensional tectonism (Archibald *et al.*, 1983). The complexity of the tectonic history is reflected in the variation of Sr isotopic compositions of the vein carbonates within this region. Throughout the Kootenay Arc, $^{87}Sr/^{86}Sr$ values of hydrothermal vein carbonate are variable and highly radiogenic, ranging from 0.7108-0.7384. These values approach the values obtained for the vein carbonates of the Miette Group in the Rocky Mountains.

In the northern part of the Kootenay Arc, vein carbonates range in $^{87}Sr/^{86}Sr$ from 0.7149 -0.7384. Two metasedimentary rocks were analysed from the Kootenay Arc. The measured $^{87}Sr/^{86}Sr$ values are 0.7167 and 0.7177. Paleozoic metasedimentary rocks have also been analysed by Ghosh (1986) (listed in Table 1). He obtained an initial $^{87}Sr/^{86}Sr$ ratio of 0.71018 ±27 for the metasedimentary rocks of the Nelway Formation. Metamorphic ages of other Paleozoic metasedimentary rocks have initial $^{87}Sr/^{86}Sr$ values that range from 0.7092 to 0.7166 (Ghosh, 1986). Because the age of the regional veins has not been determined, the Sr ratios of the metasedimetary rocks in the Kootenay Arc at the time of vein formation can not be calculated. However, the Sr data do indicate a wide range of Sr isotopic compositions for the Paleozoic clastic sequences. To a first approximation, the Sr isotopic compositions of the vein carbonates correlate broadly to the metasedimentary rocks exposed throughout the Kootenay Arc.

An additional source for the radiogenic Sr values in the veins is suggested to be the Mesozoic and Cenozoic plutons abundant in the southern Omineca belt. Plutons in this region are characterized by high initial Sr ratios (Armstrong, 1988). Armstrong (1988) has documented granitic rocks with ratios >0.710. Whether the vein-forming fluids interacted with the abundant plutonic rocks in the region is unknown; however, it is feasible that they may have been a source of radiogenic strontium observed in the vein carbonates.

In the southern part of the Kootenay Arc, samples from the vein systems and limestones hosting gold mineralization of the Sheep Creek mesothermal gold deposit (Vsc samples) were analysed. These mineralized veins range in $^{87}Sr/^{86}Sr$ from 0.71079-0.7214. Cambrian limestones which host the veins range in $^{87}Sr/^{86}Sr$ from 0.7108-0.7258. The rocks are unlike typical Cambrian limestones which have values ranging from 0.7089-0.7091 (Burke *et al.* 1982). This area of mineralization will be discussed in greater detail in the following chapter.

Quesnellia Terrane

Samples from the Slocan Group, which is comprised of Triassic argillaceous rocks with minor sandstone and carbonate, are located to the north of the Nelson batholith. Rocks in this region are situated in the hanging wall of the Slocan Lake Fault, a normal fault of Eocene age (Parrish *et al.*, 1988). Vein carbonates have $^{87}Sr/^{86}Sr$ values varying from 0.7047 to 0.7133. These veins are thought to have been formed from the hydrothermal fluids that formed the veins hosting Ag-Pb-Zn mineralization of the Slocan camp. The mineralized veins have been dated at 58-59 Ma, suggesting that the mineralization was contemporaneous with the extensional faulting event (Beaudoin *et al.*, 1992).

The possibility that several distinct fluids originating from different sources have interacted in this region has been proposed by Beaudoin *et al.* (1992). They used Pb, C, O and H isotopes to constrain the sources of solutes within the hydrothermal system associated with the Slocan mineralization. According to Beaudoin *et al.* (1992), mixing of fluids from such reservoirs as the upper crust, lower crust and the mantle has occurred in the areas of mineralization of the Slocan district. If this is the case, the observed spread in $^{87}Sr/^{86}Sr$ values in the hydrothermal veins may also be a product of mixing of fluids of lower crustal or mantle derivation (ie. 0.7047) with fluids derived from the Slocan argillites (0.7133). Alternatively, the source of the strontium may be from one hydrothermal fluid whose $^{87}Sr/^{86}Sr$ composition evolved as the fluid encountered different rock types. Lack of isotopic equilibrium with the host rocks (ie. Slocan argillites) would allow a range in Sr isotopic compositions to be present in the vein carbonates.

To the south of the Nelson batholith, two barren vein calcites were sampled from the Lower Jurassic Rossland Group. The veins occur within the Elsie Formation of the Rossland Group, which consists predominantly of basalt, andesites, and pyroclastics with lesser amounts of intercalated siltstones (Hoy and Andrew, 1991). Throughout the Rossland Group, veins are thought to be related to the intrusion of Middle Jurassic granitoids (Hoy and Andrew, 1990; 1991). $^{87}Sr/^{86}Sr$ values of 0.7061 and 0.7059 were obtained for the sediment-hosted veins. Rossland volcanic rocks and the metasedimentary rocks from the Ymir Group, which correlate closely to the Rossland Group metasedimentary rocks, have initial $^{87}Sr/^{86}Sr$ values of 0.7033-0.7040 and 0.70644±36, respectively (Ghosh, 1986). Assuming that the veins are Late Jurassic in age, the Sr composition of the volcanics would be approximately 0.7041 at the time of vein formation. Vein strontium more closely correlates to the Sr composition of the sediments, suggesting that these clastic rocks are the likely source of radiogenic vein strontium.

Veins hosted by the Slocan and Rossland sedimentary rocks have the lowest Sr isotopic compositions of all veins in the Omineca belt. Like the veins in the Kootenay Arc, these vein systems are hosted by sedimentary rocks. However, rocks of the Quesnellia terrane are comparatively younger than the Upper Paleozoic metasedimentary rocks of the Kootenay Arc to the east. The lower $^{87}Sr/^{86}Sr$ ratios of the vein carbonates in the Quesnellia terrane reflect the younger ages of the rocks.

E. Intermontane Belt

Vein carbonates from the Intermontane belt were sampled primarily from volcanic rocks that range in age from Triassic to Tertiary. Host rocks include volcanics of the Upper Paleozoic Cache Creek Group; the Triassic Nicola Group; the Spences Bridge Group, of Late Cretaceous to Paleocene age; volcanics from the White Lake area (X-samples and EE92-12,13,16); the Kettle River Formation (Paleocene to Eocene) (EE92-4); and the Eocene to Miocene Kamloops Group (AK91-10, 11, EE92-8, 10, 19).

Vein carbonates in the Intermontane belt are characterized by $0.705 < {}^{87}Sr/^{86}Sr < 0.707$. Within each formation, the strontium compositions of the veins are generally uniform; however, variations in values exist between the different formations.

Nicola Group

The Triassic Nicola Group consists mainly of andesites with associated sedimentary rocks that have undergone greenschist facies metamorphism (Smith, 1986). The timing of vein formation coincides with the time of metamorphism (Late Jurassic); both occurring as a result of the emplacement of intrusives such as the Pennask batholith, the Nicola batholith and the Douglas Lake pluton in the southern Intermontane belt (Smith, 1986). Smith (1986) and Preto *et al.* (1979) analysed the strontium isotopic ratios of the Nicola Group volcanic rocks. Although the initial ratios of these volcanic rocks failed to yield an isochron, Smith (1986) was able to estimate the initial Sr ratio to range from 0.7025-0.7042, when age of the rocks are corrected for an assumed age of 220 Ma. Preto *et al.* (1979) obtained somewhat higher initial $^{87}Sr/^{86}Sr$

values for the volcanic rocks ranging from 0.7034-0.7047. They attributed this variation in host rock composition to isotopic resetting from interstitial fluids during low grade metamorphism. Strontium isotopic data obtained for vein carbonates in this study are remarkably uniform, averaging 0.7042 ± 0.0003 (n=5). These strontium compositions of the vein carbonates correlate to the Sr values of the volcanic rocks. One limestone from this study yielded a $^{87}Sr/^{86}Sr$ value of 0.7040, whereas Nicola limestones analysed by Preto *et al.* (1979), gave Sr ratios of 0.7074 and 0.7076. Their values are consistent with Upper Triassic limestone values of 0.7074-0.7077 (Burke *et al.*, 1982). An analysis of a slate yielded a measured $^{87}Sr/^{86}Sr$ ratio of 0.7051.

The similarity in $^{87}Sr/^{86}Sr$ between the vein carbonates and the volcanic rocks of the Nicola Group indicates that vein-forming fluids incorporated strontium originating from the volcanic lithologies.

Spences Bridge Group

Veins were sampled from the Spences Bridge Group, which consists of basalts, rhyolites and clastic rocks. These rocks represent an island arc tectonic setting of Late Cretaceous age (Thorkelson *et al.* 1985). Smith (1986) obtained an initial Sr ratio of 0.70334 ± 0.00008 for the volcanic rocks. Vein calcites from this study have an average ratio of 0.7041 ± 0.0009. The vein carbonates are more radiogenic than the initial Sr value of the host basalts.

In order to determine whether the basalts could possibly have contributed Sr to the veins, the ratio in the basalts at the time of vein formation must be known. This can be calculated using the highest Rb/Sr value obtained by Smith (1986) for the basalts, and estimating the largest possible difference in age between the crystallization of the basalts and the formation of the veins. Assuming the veins to be no younger than Tertiary (50 Ma), and using the age of 115 Ma calculated by Smith (1986) for the basalts, the $^{87}Sr/^{86}Sr$ ratio present in the basalt at the time of vein formation is calculated to be 0.7034. This value is significantly lower than the measured Sr value of 0.7041 of the vein calcites. Consequently, it appears that the basalts did not solely contribute radiogenic strontium to hydrothermal fluids which formed the veins. The high values in the vein calcites may be attributed either to an external source such as sedimentary rocks, or to selective leaching from an Rb-rich phase within the basalts. However, incongruent leaching of the basalts is unlikely to have occurred because there are no Rb-rich minerals present. An additional source external to the host volcanics is required to produce the radiogenic Sr composition in the veins.

Tertiary Volcanics

Vein carbonates from the Tertiary units of the Kettle River Formation and the White Lake area (southwest of Okanagan Lake) have $^{87}Sr/^{86}Sr$ values of 0.7052 and 0.7065-0.7071, respectively.

A range of initial Sr ratios from 0.7038 to 0.7048 was obtained by Smith (1986) for the Kamloops volcanic rocks, using an approximate age of 50 Ma. $^{87}Sr/^{86}Sr$ values of hydrothermal calcites of the Kamloops volcanics average 0.7061 ± 0.0005. The veins are more radiogenic than the host rocks, indicating isotopic disequilibrium. The time elapsed between the crystallization of the host basalts and the formation of the veins is small, indicating that the increase in ^{87}Sr from the decay of ^{87}Rb is negligible. Furthermore, the present day Sr values of the volcanic rocks as measured by Smith (1986) are less than the Sr value observed in the vein calcites. Consequently, the veins have incorporated radiogenic strontium derived from an external source. The probable sources that would produce the radiogenic strontium values are regional sedimentary rock units.

Cache Creek Group

The Cache Creek Group is located near the western edge of the Intermontane belt. The rocks consist of limestone, basalt, partly serpentinized ultramafic rocks, chert, argillite and phyllite (Cordley *et al.*, 1987). The Cache Creek Group contains rocks of Pennsylvanian to Middle Jurassic in age and is considered to be of oceanic origin (Monger, 1989). Radiometric dating of basalts from the Cache Creek Group failed to yield an isochron (Smith, 1986). The scatter may be attributed to regional metamorphism in the Late Jurassic, which has altered the rocks to greenschist facies. Assuming that the rocks have a crystallization age of 300 Ma, initial $^{87}Sr/^{86}Sr$ ratios were calculated to range from 0.7039 to 0.7048 (Smith, 1986).

Vein carbonates within the volcanic rocks have a mean $^{87}Sr/^{86}Sr$ value of 0.7058 ± 0.0002. The hydrothermal carbonates are slightly more radiogenic than the host basalts, which does not preclude the volcanics as possibly contributing Sr to the fluids, but suggest an additional component of Sr derived from an external source. Using data from Smith (1986), calculations of the Sr composition of the basalts at the maximum possible age difference of the host rock and the veins (250 Ma) indicate that the Sr composition would not have been greater than 0.7051 at the time of vein formation. This value is less than the vein Sr values. As was suggested with the veins from the Spences Bridge Group and the Kamloops Group, hydrothermal fluids may have scavenged Sr from such sources as regional sedimentary lithologies prior to traveling through the host volcanic rocks. In particular, the fluids may have incorporated strontium from the limestones which are prevalent in the region.

In summary, strontium ratios of vein calcites hosted by Late Cretaceous to Tertiary volcanic rocks in the Intermontane belt span a range from 0.7035 to 0.7072. The Sr isotopic compositions of the veins hosted by the Nicola Group correlate with the host volcanic rocks. Although the predominant sources of Sr are volcanic host rocks, an additional source of Sr from sedimentary rocks is suggested for veins hosted by the Spences Bridge Group, the Kamloops Group and the Cache Creek Group.

F. Fraser Fault Region

Among the lowest Sr ratios obtained for vein carbonates in the southern Canadian Cordillera are the veins of the Fraser Fault region. The faults in this area mark the boundary between the Intermontane belt to the east and the Coast Plutonic belt to the west. The major faults - Fraser, Hozameen, Pasayten, and Yalakom faults, of Late Cretaceous to early Tertiary age, are right lateral strike-slip faults. Faulting has caused displacement of rocks northward for an estimated distance of 150 km northward (Monger, 1989). The veins sampled in this region are hosted by sedimentary and metamorphic rocks.

Jackass Mountain Group

The Jackass Mountain Group consists of conglomerates, turbidites, shales and sandstones. The assemblages represent Jurassic to Cretaceous sedimentation in the Tyaughton-Methow basin (Kleinspehn, 1985). The conglomerates contain abundant volcanic clasts from the Spences Bridge Group and plutonic clasts from the adjacent Mount Lytton Complex (Kleinspehn, 1985). An average strontium value of 0.7042 ± 0.0007 (n=5) was obtained for the vein calcites. This value is lower than would be expected for veins hosted by rocks of sedimentary compositions. Mesozoic and Cenozoic plutons in this region commonly have initial ratios of 0.703-0.7044 (Table 1) and may have been the source of Sr in fluids circulating through crustal rocks. Because the age of vein formation is not known and there is no Sr data on rocks from the Jackass Mountain group, the source of strontium can not be determined.

Bridge River Group

The Bridge River Group, lying to the west of the Fraser and Yalakom faults, is an oceanic assemblage comprising of pillow basalts, volcaniclastic rocks, chert and argillite (Rusmore *et al.*, 1988). The Bridge River terrane contains rocks of Permian to Jurassic in age and was accreted to the margin of North America in the Middle Jurassic. The strontium systematics of the pelitic sediments of the Bridge River Group have been reset by metamorphism which took place in the Late Jurassic (Leitch *et al.*, 1991). The reset initial Sr value of the metasedimentary rocks range from 0.7050 to 0.7060.

Vein calcites have an average ratio of 0.7048 ± 0.0011. If the veins are related to the metamorphic event, then the strontium ratios incorporated the strontium signatures of the regional metasedimentary rocks. Plutonic rocks in the Fraser Fault region have initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.703 to 0.704 (Armstrong, 1988; Greig *et al.*, 1992). A magmatic component may also be present in the vein carbonates if the vein-forming fluids circulated through plutonic and volcanic rocks prior to migrating through the host sedimentary rocks.

Ladner Group

One vein sampled from the Ladner Group in the Methow terrane has a $^{87}Sr/^{86}Sr$ value of 0.7046. It is hosted by Lower Jurassic argillites and siltstones. Proximal to the metasedimentary rocks is the Needle Peak pluton to the east, which has been dated at 22±4 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7036±0.0001 (Greig *et al.*, 1992). If the vein is younger than the pluton, the vein-forming fluids may well have derived its Sr composition from the pluton, or may have been modified by circulation near the pluton.

In summary, these regional, barren vein systems have low Sr isotopic compositions that are generally <0.705. The Sr isotopic compositions of vein carbonates are slightly higher than the initial $^{87}Sr/^{86}Sr$ ratios of the plutonic and volcanic rocks. This may be explained by: 1) vein-forming fluids circulating solely through the metasedimentary rocks of the region; 2) mixing of Sr in fluids perhaps originating from magmatic sources and interacting with sediments in the region; 3) a magmatic source with selective leaching from an Rb-rich mineral. The third explanation is the least likely to have occurred since incongruent leaching is not a likely possibility. However, the Sr isotopic compositions are not conclusive to eliminate the second explanation. The first suggestion is the most probable because the veins are hosted by the metasedimentary rocks.

VI. ISOTOPIC GEOCHEMISTRY OF MINERALIZED VEINS

A. Introduction

Zones of mineralization present a unique case for tracing strontium isotopic compositions. These zones often represent areas of locally high fluid flux within larger hydrothermal systems. High water/rock ratios in these zones increase the likelihood that the isotopic signatures of the fluids buffer the rock composition.

The principle objective of this part of the study is to determine whether differences in Sr isotopic compositions exist between veins within mineralized zones and barren veins regional to the deposits. Such differences may provide constraints on the genetic models associated with these deposits. Distinct isotopic signatures can be used as a guide to exploration.

Mineralized veins from the following hydrothermal ore deposits were sampled: 1) Cariboo mesothermal gold district; 2) Sheep Creek mesothermal gold camp; 3) Phoenix-Greenwood copper skarn deposits; 4) Vault epithermal gold deposit. The locations of these deposits are shown on Figure 14. Table 5 lists the $^{87}Sr/^{86}Sr$, $\delta^{18}O$ and $\delta^{13}C$ data of vein carbonates from the ore deposits and from locations distal to the deposits. Stable isotope data on the mineralized vein systems of the Cariboo, the Sheep Creek district and the Vault property have been compiled from Nesbitt *et al.* (1989), Zaluski (unpublished data), Hardy (1992) and Xiong (1993) respectively.

B. Cariboo Gold District

The Cariboo gold district is located within the autochthonous Barkerville subterrane in the Omineca belt. The mesothermal gold deposits of this district are hosted primarily by metamorphosed limestones and basalts of the Late Proterozoic to Paleozoic Snowshoe Group (Struik, 1988). The ore occurs within quartz-carbonate veins and as replacement bodies in the limestones. Gangue calcite, dolomite and ankerite occur in the hydrothermally altered zones along with quartz, albite and sericite (Struik, 1988; Nesbitt and Muehlenbachs,

Table 5 Strontium, oxygen and carbon isotopic data for mineralized carbonate veins

Unit and Sample[1]	Mineral	$^{87}Sr/^{86}Sr$	$\pm 2\sigma$ $(\bullet 10^{-5})$	$\delta^{18}O$ ‰SMOW	$\delta^{13}C$ ‰PDB
Cariboo District[2]					
Mineralized veins					
CR4	calcite	-	-	14.5	-7.3
CR5	calcite	-	-	13.4	-2.1
CR 6a	calcite	0.71110	24	-	-
CR 9	calcite	0.71447	6	-	--
CR 10	calcite	0.71611	6	13.7	-5.7
CR 13	calcite	0.72166	24	-	-
Regional veins					
C45	calcite	0.70964	13	1.4	-1.9
C46	calcite	0.70890	4	17.4	-3.4
C47a	marble	0.70880	4	23.6	-0.8
C48	calcite	0.70882	4	23.3	-0.1
Sheep Creek gold camp					
Vsc 081	calcite	0.71574	9	11.1	-2.2
Vsc 315	limestone	0.72581	2	18.9	-1.4
Vsc 352	calcite	0.71079	5	20.3	-1.0
Vsc 353	limestone	0.71080	5	20.1	-1.3
Vsc 355	calcite	0.72145	5	16.3	-2.6
Vsc 357	calcite	0.71155	3	17.6	-3.2
Vsc 357b	calcite	0.71472	4	15.5	-1.1
Vsc 358	limestone	0.70959	8	22.7	-1.2
Vsc 421	limestone	0.71582	18	20.7	-1.5
Greenwood District					
AK90-19	calcite	0.70603	10	14.3	-7.8
AK90-21	calcite	0.70505	10	12.8	-
AK90-23	calcite	0.70645	2	11.2	-6.3
AK90-24	calcite	0.70586	4	9.4	-5.8
AK90-25	calcite	0.70828	8	2.0	-3.7
AK90-27	calcite	0.70627	10	15.0	-9.4
Vault epithermal gold deposit					
Mineralized veins					
X-19	calcite	0.70712	24	7.4	-5.1
X-118	calcite	0.70708	6	5.9	-5.9
X-38b	calcite	0.70706	2	4.0	-5.8
X-11	andesite	0.70710	4	-4.0	-
X-46c	andesite	0.70938	2	3.4	-
Regional veins					
EE92-12	calcite	0.70695	4	-	-
EE92-13	calcite	0.70654	3	-	-
EE92-16	calcite	0.70715	8	-	-

Notes:

[1] Sample in bold type indicates analysis of host rock.

[2] Oxygen and carbon data from the Cariboo district is from Nesbitt *et al.*, (1989), and Zaluski (unpublished data), mineralized veins in the Sheep Creek deposit from Hardy (1992), and the Vault property from Xiong (1993).

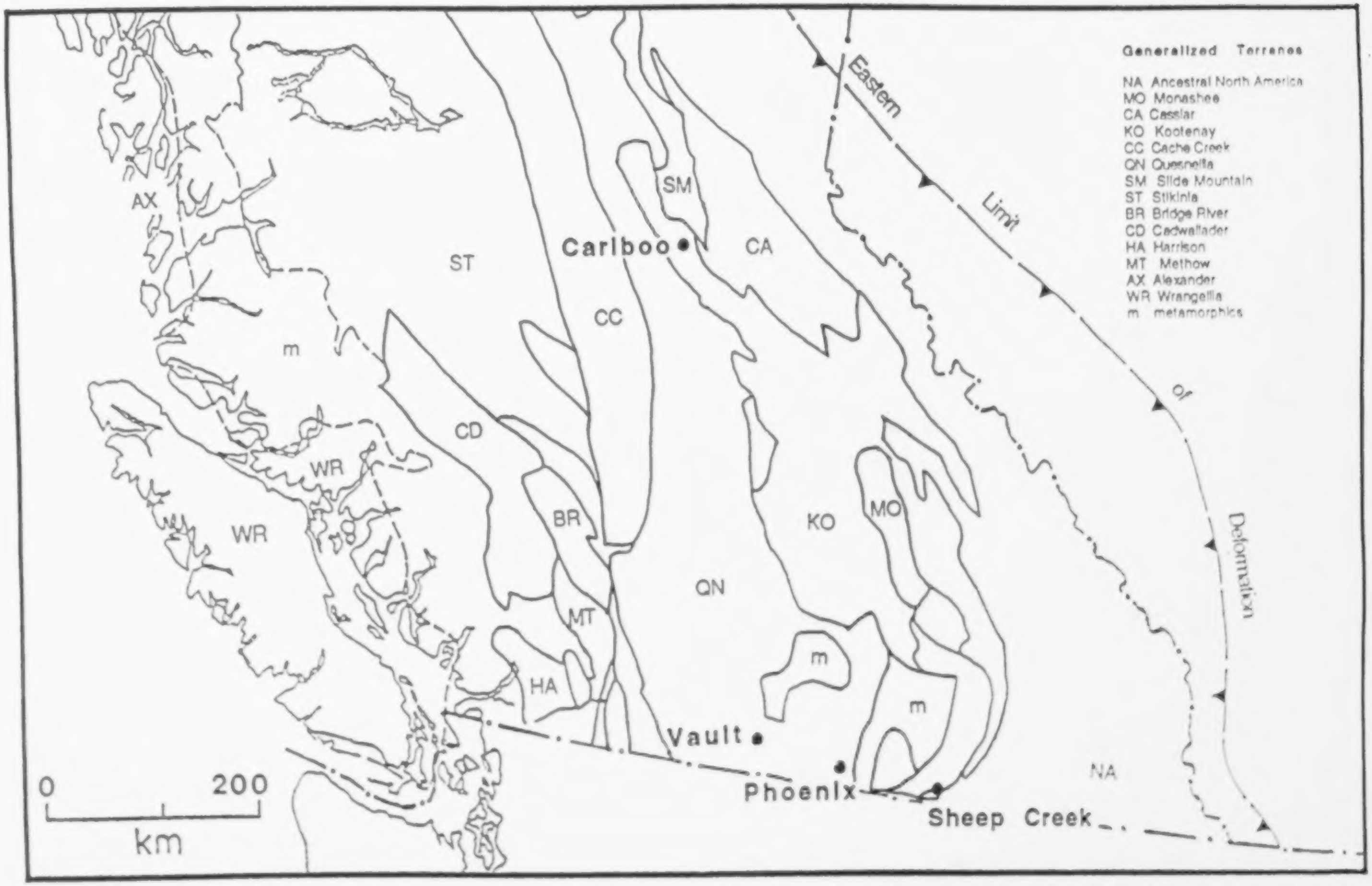

Generalized Terranes
NA Ancestral North America
MO Monashee
CA Cassiar
KO Kootenay
CC Cache Creek
QN Quesnellia
SM Slide Mountain
ST Stikinia
BR Bridge River
CD Cadwallader
HA Harrison
MT Methow
AX Alexander
WR Wrangellia
m metamorphics
Eastern Limit of Deformation
Cariboo
Vault
Phoenix
Sheep Creek
NA
ST
CC
SM
CA
KO
MO
QN
CD
BR
MT
HA
WR
WR
AX
m
m
m
0
200
km

Figure 14 Map showing locations of deposits analysed in this study (modified after Gabrielse *et al.*, 1991).

1989b). The mineralization has been dated at 141±5 Ma by K-Ar methods (Andrew *et al.*, 1983).

Vein carbonates of the Cariboo Gold district span a wide range of stable isotope compositions. Mineralized vein carbonates have $\delta^{18}O$ values ranging from 13.4 to 14.5‰. No host limestones were analysed. However, if compared to typical values for contemporaneous limestones ($\delta^{18}O$ =20-23‰, Veizer, 1983), these mineralized vein carbonates are depleted in ^{18}O. The $\delta^{13}C$ values of these samples, spanning a range of -7 to -2.1‰ (Nesbitt and Muehlenbachs, 1989b), may also differ from typical Proterozoic host limestones ($\delta^{13}C$ =0 ±4‰, Ohmoto, 1986). In contrast, regional vein carbonates have $\delta^{18}O$ compositions that range from 17.4-23.3‰, and $\delta^{13}C$ values that range from -0.1 to -3.4‰ (Zaluski, unpubl. data). These values are consistent with derivation from Late Proterozoic - Early Paleozoic marine limestones, which range from $\delta^{18}O$ = 20-23‰ (Veizer, 1983) and $\delta^{13}C$= -4 to +4‰ (Ohmoto and Rye, 1979)

Strontium isotopic compositions also vary between these two types of vein carbonates. $^{87}Sr/^{86}Sr$ values of mineralized veins are variable, ranging from 0.7111 to 0.7217. In contrast, strontium isotopic ratios of vein carbonates from surrounding country rocks are less variable, with an average $^{87}Sr/^{86}Sr$ value of 0.7091 ± 0.0004 (n=3). One limestone located proximal to the barren veins yielded a $^{87}Sr/^{86}Sr$ value of 0.7088 which is in good agreement with values obtained for other late Proterozoic - Early Cambrian limestones ($^{87}Sr/^{86}Sr$=0.7070-0.7093, Veizer *et al*, 1983; Burke *et al.*, 1982). This is consistent with the interpretation that Sr in the regional veins are derived from host limestones. It is evident that mineralized veins have Sr isotopic compositions that are more radiogenic than regional limestones. Although no wall rock limestones were available for analysis, it is suggested that the mineralized veins may be in disequilibrium with wall rock limestones. Probable sources for strontium from mineralized veins are the clastic metasedimentary rocks of the Snowshoe Group.

The different strontium isotopic compositions of the mineralized and unmineralized vein carbonates can be explained either in terms of differing amounts of fluid flux during vein formation or in terms of the relative proximity of each to the regional metasedimentary rocks. The mineralized veins are in close proximity to fault systems which are associated with major strike-slip faults (Nesbitt *et al.*, 1989b). The association of these deposits with large fault structures and smaller secondary fracture sets would allow for greater amounts of fluid from deeper regions in the crust to be involved in the mineralizing process. The channelized fluid flow in the mineralized zone may be of a significant size to preserve the Sr ratio derived from the clastic rocks during transport and deposition of vein calcite in the limestones. In contrast, regional barren veins are located further from the immediate fault zone. A pervasive fluid flow through the limestones would cause greater water/rock interaction, allowing for limestone Sr isotopic compositions to be incorporated into the regional vein carbonates.

Alternatively, the regional veins may be located closer to the clastic sequences than the mineralized veins. Both types of veins are hosted by limestones; however, the areal extent of the limestone units may differ.

C. Sheep Creek Gold Camp

The mesothermal Sheep Creek deposit is located southeast of Salmo in the southern Kootenay Arc. Gold mineralization occurs in large quartz veins within various Cambrian sequences including the Quartzite Range Formation, Reno Formation and the Laib limestone (Hardy, 1992). The veins show a close spatial relationship to major normal faults and secondary fractures. Quartz, pyrite and sphalerite constitute the majority of the vein material; calcite, siderite and galena and gold are present in minor amounts. Veins that contain calcite are usually located near or adjacent to the host limestones (Hardy, 1992).

Vein carbonates within the deposit vary in $\delta^{18}O$ from 14 to 21‰, with a mean value of 16.8±2.7‰ (n=5) (Hardy, 1992). Host limestones yield $\delta^{18}O$ values ranging from 18.9 to 22.7‰, with a mean value of 20.5±1.1‰ (n= 4). These $\delta^{18}O$ values indicate that the vein carbonates are depleted in ^{18}O relative to the limestones. Vein $\delta^{13}C$ values average -2.5±1.3‰, which correlate closely to the average $\delta^{13}C$ value of -1.9±2.4‰ for the limestones (Hardy, 1992). Whereas the carbon isotopic compositions indicate isotopic equilibrium between the vein carbonates and the limestones, the oxygen isotopic compositions indicate disequilibrium conditions.

$^{87}Sr/^{86}Sr$ values of the mineralized veins span a large range (0.7109 to 0.7214) which overlaps the range for the host limestones (0.7096 to 0.7258).

These limestone Sr values are higher than "normal" strontium ratios of unaltered Cambrian limestones (0.7089-0.7093, Burke *et al.*, 1982) and indicate that the rocks have been reset by external fluids.

Other isotopic studies have documented large scale fluid flow systems in the Sheep Creek District. Oxygen isotopic exchange between hydrothermal fluids and country rocks has been documented in the nearby Nelson batholith (Margaritz and Taylor, 1986). Reset K-Ar dates on other plutons in the immediate vicinity of the deposit provide further evidence for hydrothermal alteration within this region (Archibald *et al.*,1983). It is feasible that the radiogenic strontium found in the limestones was a result of the same hydrothermal event noted in the plutons. An alternate possibility is that the strontium isotopic variability of the limestones reflect local interactions between hydrothermal fluids and metasedimentary rocks adjacent to the limestones. The lack of a corresponding oxygen depletion in the limestones may suggest that this is the case. The proximity of the metasedimentary rocks to the limestones needs to be investigated in detail.

Unlike the Cariboo mineralized veins, the high $^{87}Sr/^{86}Sr$ values in the mineralized vein carbonates of the Sheep Creek deposit broadly correlate to the Sr isotopic compositions of the barren vein carbonates occurring throughout the southern part of the Kootenay terrane. These regional veins are hosted predominantly by Upper Paleozoic metasedimentary rocks. $^{87}Sr/^{86}Sr$ ratios of 0.7167 and 0.7176 were obtained for two host rocks. These sedimentary sequences are a likely source of radiogenic strontium for the mineralized veins and the limestones of the Sheep Creek deposit.

D. Phoenix Copper-Gold Skarn

The deposits in the Phoenix camp, east of the town of Greenwood, are predominantly copper-gold skarns. The Triassic Brooklyn Group, which consists of limestone, conglomerate, shale, and volcanic rocks, is host to the majority of the skarns in this region (Church, 1986). Skarnification of the limestone was caused by the emplacement of the Wallace Creek granodiorite in the Late Cretaceous. Several styles of mineralization are present, including vein systems and replacement of wall rocks. Mineralization of the Cu-Au skarns consists of pyrite, chalcopyrite, magnetite and pyrrhotite (Ettlinger and Ray, 1988).

Chemical analyses provide evidence that elemental exchange between the Wallace Creek pluton and the Brooklyn limestone has occurred (Church, 1986).

Vein calcites have $\delta^{18}O$ values ranging from 2.0 to 15.0‰, with the majority of analyses >9.4‰. No oxygen compositions of limestones from the Brooklyn Formation are available. The vein $\delta^{18}O$ values do not differ from $\delta^{18}0$ values obtained for other vein carbonates within the southern Omineca belt.

$\delta^{13}C$ values of these mineralized veins range from -5 to -9‰. These values are lower than values obtained from marine limestones ($\delta^{13}C$= -4 to +4‰, Ohmoto and Rye, 1979) and suggest a contribution from a source in addition to the limestones.

Strontium isotopic compositions of the mineralized veins range from 0.7050 - 0.7083. Since typical Triassic limestones range from 0.7076 to 0.7078 (Burke *et al.*, 1982), the mineralized veins may have similar Sr isotopic composition to the Triassic Brooklyn limestones. Magmas that intruded the south-central Omineca belt during the Late Cretaceous typically have initial $^{87}Sr/^{86}Sr$ values >0.704 (Armstrong, 1988). It is reasonable to assume that the isotopic composition of the Wallace Creek pluton is also >0.704. Because the Rb content of clastic sediments is high (Faure, 1986), the clastic units associated with the Brooklyn formation are likely to contain more radiogenic strontium than the limestones. Given the above constraints, it is likely that the strontium in the veins is derived from either the local limestones, local igneous rocks or a combination of the two. Since strontium ratios of Triassic age limestones are > 0.7076, the vein Sr values that are <0.7076 indicate an igneous source.

E. Vault Epithermal Gold Deposit

The Vault property lies to the southwest of Okanagan Lake at the eastern edge of the Intermontane belt. It is classified as an adularia-sericite type deposit (Meyers, 1989). Rocks hosting the gold mineralization are Tertiary volcanic rocks, predominantly trachytic in composition, and have undergone argillic, propylitic and silicic alteration (Xiong, 1993). Mineralization occurs in two forms: as stockwork ore with abundant sulfides; and as ore within quartz-carbonate veins (Xiong, 1993).

Mineralized calcite veins exhibit a wide range of $\delta^{18}O$ from -3.6 to +13.7‰. Veins showing the greatest ^{18}O depletion are late stage quartz-calcite veins (Xiong, 1993). Regional carbonate veins have $\delta^{18}O$ values of -3.8 to +15.5‰.

The $\delta^{13}C$ values of vein calcites vary from -12.5 to -4.5‰. A magmatic signature (-5 to -8‰) is apparent in trachyte hosted veins whereas an organic carbon signature (<-10‰) is noted in veins hosted by mudstones (Xiong, 1993). The carbon data show a strong correlation to the lithology of the host rock. Regional vein carbonates hosted by Tertiary volcanic rocks have carbon values ranging from -15 to -4.3‰ (Xiong, 1993).

Mineralized calcite veins have uniform Sr compositions with an average value of 0.70710 ± 3. Barren veins in surrounding country rocks have ratios averaging 0.70690 ± 3. Consequently, for oxygen, carbon and strontium isotopes, there are no significant differences between mineralized and regional vein calcites.

Sample X-46c, a trachyte from the Vault property has a measured Sr ratio of 0.7094. Estimating a maximum age of mineralization to be 45-50 Ma (Xiong, 1993), the $^{87}Sr/^{86}Sr$ ratio of the trachyte at time of vein formation was 0.7081. Sample X-11 is a propylitic trachyte from the Dusty Mac epithermal deposit, located a few kilometers to the east, and has a measured $^{87}Sr/^{86}Sr$ value of 0.70710. However, accurate $^{87}Rb/^{86}Sr$ value was not obtained and consequently, no estimate of the $^{87}Sr/^{86}Sr$ ratio at the time of vein formation was possible. The similarity in values between the veins and the host volcanics strongly suggests that these rocks are the source of the vein strontium.

Xiong (1993) showed that water/rock ratios in the zones of mineralization are low (w/r~1.5). He also concluded that while the hydrothermal system was channelized on a regional scale, it was pervasive on a smaller scale within the mineralized areas. These factors and the close correlation of $\delta^{13}C$ values between the veins and the host rocks led Xiong (1993) to suggest that the volcanic rocks have buffered the carbon compositions of the fluids. The similarity in $^{87}Sr/^{86}Sr$ between the veins and the host rocks further suggests that fluids incorporated both strontium and carbon isotopic compositions of the local volcanic rocks.

F. Interpretation of Isotopic Data of Mineralized Veins

In portions of the mesothermal gold deposits of the Cariboo and the Sheep Creek district, and in the Phoenix skarn deposits, the mineralized veins are hosted by limestones. In the Sheep Creek and Phoenix deposits, the oxygen isotopic compositions of mineralized vein carbonates are depleted relative to the $\delta^{18}O$ values of the host rocks. In the Vault epithermal gold deposit, the late stage calcite veins are depleted relative to the main stage calcite veins, but are in good agreement with the whole-rock $\delta^{18}O$ values of the host volcanic rocks, which also show a depletion in ^{18}O (Xiong, 1993).

Carbon isotopic compositions of veins associated with mineralization reflect isotopic compositions of the host rocks in the Sheep Creek deposit and the Vault property. The source of carbon in the skarns of the Phoenix-Greenwood deposits was not determined. In the Cariboo district, carbon values are slightly lower than the host limestones and reflect an external source. Furthermore, of the four mineralized vein deposits, this district alone has vein $\delta^{13}C$ values that are markedly different from regional barren veins.

With the possible exception of the Cariboo district, strontium compositions of mineralized veins reflect local host rock compositions. The calcites in the mesothermal gold deposit of the Cariboo district contain anomalously high strontium isotopic ratios (0.7111-0.7217) relative to regional veins and regional limestones. The Sr isotopic composition of the limestones hosting the mineralized veins is not known. Regional limestones have Sr ratios that are consistent with the isotopic compositions of limestones of similar ages ($^{87}Sr/^{86}Sr$ = 0.7070-0.7093 for typical Late Proterozoic - Early Cambrian limestone values, Veizer *et al.*, 1983; Burke *et al.*, 1982). The large ranges in strontium isotopic compositions exhibited by the mineralized veins of the Cariboo (0.7111- 0.7217) and Sheep Creek (0.7109- 0.7214) districts indicate that either the composition of the hydrothermal fluids was not uniform over the time of mineralization or local variations in strontium are present in the contiguous host rocks.

Mineralizing fluids associated with the Cu-Au skarn deposits at the Phoenix camp have a complex history that cannot be deciphered by isotopic characterization alone. Strontium isotopic values suggest that vein carbonates contain both a magmatic component and a component derived from the Brooklyn limestones.

Whereas the Cariboo limestones reflect unaltered Sr signatures, the limestones of the mesothermal gold deposits in the Sheep Creek district contain anomalous strontium compositions. This may be explained by channelized fluid flow through faults in the Cariboo gold deposits versus local pervasive flow in the Sheep Creek district. The Sr isotopic composition of volcanic rocks hosting mineralization of the Vault property correlate with the initial $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks in this region (Armstrong and Ghosh, 1990).

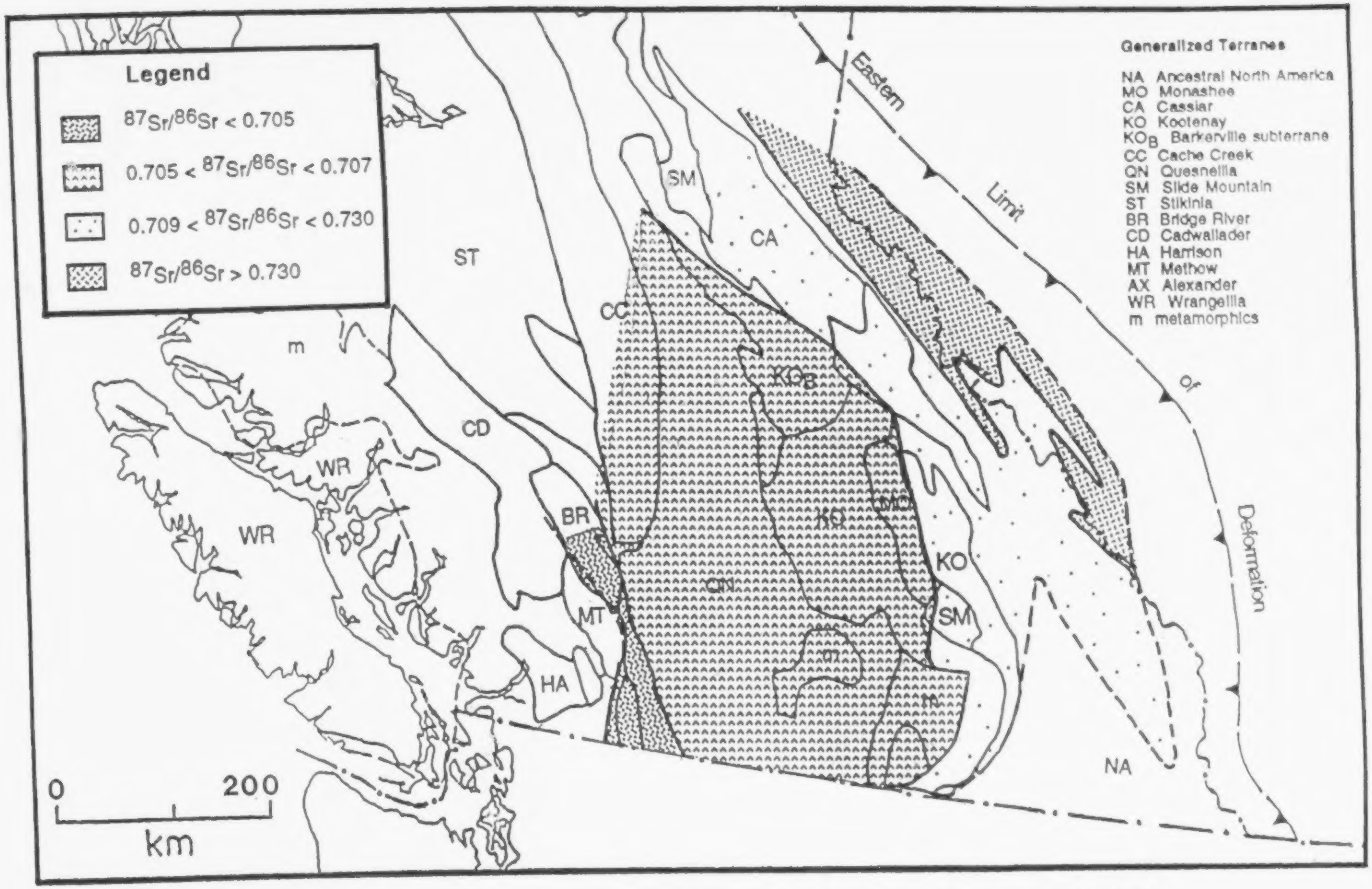
VII. DISCUSSION

A. General Trends across the southern Canadian Cordillera

A systematic trend in $^{87}Sr/^{86}Sr$ values of vein carbonates was observed across the southern Canadian Cordillera. From the Fraser Fault region to the Rocky Mountain belt, vein carbonates show a general west-east gradient of increasing $^{87}Sr/^{86}Sr$ values. These geographical variations in the strontium isotopic compositions of the vein carbonates are contoured in Figure 15. Sr ratios of vein carbonates generally <0.705 occur in the Fraser Fault region. Vein carbonates in the Intermontane belt and the western section of the Omineca range from 0.705-0.707. In the eastern section of the Omineca, Sr ratios increase dramatically and become more variable. Specifically, Sr ratios generally ranging from 0.709 to 0.725 are present in the Kootenay Arc and in the mineralized veins of the Cariboo mesothermal gold deposit. The transition in $^{87}Sr/^{86}Sr$ ratios from ≤0.707 to ≥0.709 occurs approximately at the trace of the Slocan Fault and its northern extension, the Columbian River Fault. The faults mark the boundary between the autochthonous and pericratonic terranes to the east (ancestral North America, Kootenay terrane) from the allochthonous terranes to the west (Quesnellia, Cache Creek, Bridge River). Further to the east, vein carbonates hosted by Paleozoic lithologies in the Rocky Mountain belt vary from 0.709 to 0.730. $^{87}Sr/^{86}Sr$ ratios above 0.730 are confined to the Proterozoic Miette Group. The trend reflects the increasing $^{87}Sr/^{86}Sr$ values in the easterly progression to older, more abundant sialic rocks.

The gradient is analogous to the gradient of increasing $^{87}Sr/^{86}Sr$ values observed by both Armstrong (1988) in the plutons and volcanic rocks of the Canadian Cordillera, and Kistler and Peterman (1973) in the batholiths of California. Increasing $^{87}Sr/^{86}Sr$ ratios were attributed by these authors to an increasing crustal component incorporated into the magmas. Armstrong (1988) showed that initial $^{87}Sr/^{86}Sr$ ratios of plutons in the Intermontane and Coast Plutonic belts are <0.704, whereas plutons on the Omineca and Rocky Mountain belts are >0.704, and can be as high as 0.730.

The $\delta^{18}O$ and $\delta^{13}C$ values of vein carbonates across the southern Canadian Cordillera do not vary sympathetically with the change in $^{87}Sr/^{86}Sr$


Legend
87Sr/86Sr < 0.705
0.705 < 87Sr/86Sr < 0.707
0.709 < 87Sr/86Sr < 0.730
87Sr/86Sr > 0.730
0
200
km
Generalized Terranes
NA Ancestral North America
MO Monashee
CA Cassiar
KO Kootenay
KOB Barkerville subterrane
CC Cache Creek
QN Quesnellia
SM Slide Mountain
ST Stikinia
BR Bridge River
CD Cadwallader
HA Harrison
MT Methow
AX Alexander
WR Wrangellia
m metamorphics
Eastern Limit of Deformation
ST
CD
WR
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m
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MT
HA
CC
SM
CA
KOB
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SM
QN
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m
NA

Figure 15 Simplified terrane map of the southern Canadian Cordillera showing $^{87}Sr/^{86}Sr$ contours of vein carbonate (modified from Gabrielse *et al.*, 1991).

values. High $\delta^{18}O$ values in vein carbonates occur in the Paleozoic sequences in the Rocky Mountains (16-21‰), in the Kootenay Arc (14-20‰), and to the west of the Fraser Fault zone (15-20‰). The lowest $\delta^{18}O$ values of vein carbonates are observed throughout the Intermontane belt, ranging from 2 to 15‰.

Carbon isotopic investigations indicate that in general, carbon has isotopically equilibrated with the host rocks. Consequently, a local carbon signature was evident in the vein calcites across the Cordillera. To a first approximation, low values are found in both the eastern and western sections of the southern Canadian Cordillera, namely, in the clastic Proterozoic sequences of the Rocky Mountains ($\delta^{13}C$ = -13 to -3‰), and in the Fraser Fault region ($\delta^{13}C$ = -11 to -4‰). The highest $\delta^{13}C$ values occur in the vein carbonates of the Paleozoic sequences ($\delta^{13}C$ = -2 to 0‰).

An east to west decreasing trend in measured Sr ratios is also observed in the shales and phyllites that were analysed in this study. Table 6 summarizes the measured $^{87}Sr/^{86}Sr$ values for these rocks, listed by geographic location from east to west.

Table 6 Strontium compositions of clastic rocks

Group	Sample	$^{87}Sr/^{86}Sr$	Rock Type	Age of Rock
Miette Gp	RB562	0.7560	slate	Proterozoic
	RB567	0.7783	slate	Proterozoic
Chancellor Fm	RB707	0.7188	shale	Cambrian
Kootenay Arc	AK91-4a	0.7167	phyllite	Cambrian
	AK91-5a	0.7177	phyllite	Cambrian
Nicola Gp	AK91-6a	0.7051	slate	Triassic
Jackass Mtn Gp	AK91-16a	0.7035	phyllite	Jurassic

Clastic rocks contain detrital minerals that retain the $^{87}Sr/^{86}Sr$ isotopic composition characteristic of the source rock from which they were derived (Faure, 1986). The clastic rocks become younger with progression to the west, and the detrital minerals that constitute the rock were derived from progressively younger rocks. The source of the detrital minerals in the shales of the Miette Group and the clastic rocks of the Chancellor Formations is likely to be the older crustal rocks of the Precambrian Shield. In contrast, the sources for the detrital minerals in the sedimentary rocks to the west are typically younger rocks. For example, the clasts of the Jackass Mountain sedimentary rocks in the Fraser Fault region were derived from the Mesozoic Spences Bridge Group and the Mount Lytton complex (Kleinspehn, 1985). Consequently, the Sr ratios in the clastic rocks become, to a first approximation, progressively lower.

B. Mineralized Veins

The mesothermal gold deposits in the Kootenay terrane (Cariboo, Sheep Creek) feature isotopic characteristics that appear to differ from regional isotopic signatures. In terms of $\delta^{18}O$ compositions, the mineralized vein carbonates are depleted in ^{18}O relative to the host limestones. The vein carbonates of the Sheep Creek deposit have Sr isotopic compositions that are consistent with regional veins and with host rock carbonate Sr compositions. However, the unusual feature is the radiogenic limestone which host the mineralized veins. These rocks are substantially enriched in radiogenic Sr in relation to "normal" unaltered Cambrian limestones.

A similar situation appears to exist in the mesothermal gold deposit of the Cariboo district. Oxygen, carbon and strontium isotopic values of mineralized vein carbonates all appear to differ from regional vein carbonates. $\delta^{18}O$ and $\delta^{13}C$ values of the mineralized veins are depleted relative to the unmineralized veins. Mineralized carbonate veins are substantially enriched in radiogenic strontium (0.7111-0.7217) relative to regional barren veins (0.7088-0.7096), and also differ in $^{87}Sr/^{86}Sr$ from regional limestones (0.7091). Limestones hosting the mineralization were not analysed. If these limestones have typical marine limestones Sr compositions of Late Proterozoic to early Cambrian age (0.7070-0.7093, Veizer *et al.*, 1983; Burke *et al.*, 1982), then there exists extreme disequilibrium in carbonate between the veins and the limestones. However, if the limestones also record variable $^{87}Sr/^{86}Sr$ values, as is the case in the Sheep Creek district, then the mineralizing fluids have reset the Sr isotopic compositions of local limestones relative to the regional limestones. In either case, the possible sources of radiogenic strontium are the pelites and grits of the Cariboo district, which implies that fluids have transported Sr on a minimum scale of meters without reaching isotopic equilibrium.

In addition to these deposits, unusual isotopic characteristics of vein carbonates have been documented in the McDame mesothermal gold deposit in the Cassiar district (Nesbitt *et al.*, 1989a). Late stage carbonate veins show marked $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ disequilibrium with host basalts of the Sylvester Group. Vein carbonate $\delta^{18}O$ values are close to 0‰, indicating depletion in ^{18}O relative to the volcanic host rocks (Nesbitt *et al.*, 1989a). $^{87}Sr/^{86}Sr$ values of vein carbonates, which range from 0.7123-0.7133, are in contrast to the Sr isotopic compositions of the basalts, which have an estimated Sr isotopic composition of 0.702-0.703 at the time of mineralization (Nesbitt *et al.*, 1989a). No unaltered host basalts were available for analysis. The vein carbonates have clearly incorporated Sr derived from an external source. The authors suggest that the vein-forming fluids moved through the underlying sedimentary rocks prior to ascending through the basalts of the Sylvester allochthon.

The source of carbon and strontium in vein carbonates of the epithermal gold deposit on the Vault property is consistent with a local source derived from the volcanic rocks. The mineralized vein carbonates and the unmineralized regional vein carbonates have similar O, C, and Sr isotopic compositions.

The Greenwood copper-gold skarn deposit is host to two contrasting Sr regimes. Preliminary work suggests that both the Wallace Creek pluton and the Brooklyn limestone contributed Sr to the mineralizing fluid. The veins, characterized by $^{87}Sr/^{86}Sr$ values ranging from 0.705 to 0.708, have incorporated $^{87}Sr/^{86}Sr$ values that bracket the two likely sources of Sr.

This study has examined only a few zones of vein mineralization in the Canadian Cordillera. Clearly, it is necessary to examine Sr isotopic compositions of other vein deposits before generalizations can be made with respect to the relationship between ore fluids and regional fluids. The isotopic compositions of minerals associated with mesothermal gold deposits suggest local aberrations within larger hydrothermal fluid systems. Other mesothermal gold deposits within the Canadian Cordillera may feature similar anomalous isotopic characteristics. These deposits in particular, are amenable to Sr isotopic tracing because of the potential for distant transport of fluids within the major strike-slip faults that are associated with these deposits (Kerrich *et al.*, 1987). More detailed work is necessary to fully trace fluid pathways in such systems as skarn deposits, where complex fluid pathways associated with ore genesis exist.

C. Water-rock Interactions

Chemical and isotopic exchange between fluids and rocks is dependent on several parameters. These parameters include: 1) the relative chemical and isotopic concentrations of the fluids and the rocks; 2) the water:rock ratio; 3) the extent to which the system is open or closed; 4) the type of fluid flow (pervasive or channeled); 5) flow velocities; 6) porosity; and 7) the solubility of the rock. The solubility in turn is affected by such factors as temperature, pressure, pH, and Eh (Veizer, 1983; Banner and Hanson, 1990).

High water:rock ratios increase the possibility that the Sr concentration of the fluid alters the Sr composition of the wall rocks. Conversely, low water:rock ratios increase the chance that the rocks buffer the compositions of the fluid. Strontium concentrations in crustal fluids can vary greatly. Meteoric waters are relatively Sr - poor while brines are relatively Sr - rich (Drever, 1982). In dilute hydrothermal fluids, higher water:rock ratios are needed to reset wall rock strontium values than to reset oxygen values because of the smaller quantity of strontium in the fluids (Banner and Hanson, 1990).

An investigation into the water:rock ratios that may exist in areas where the Sr isotopic composition of rocks have been altered by hydrothermal fluids has been undertaken. Two Miette limestones were chosen to be modeled because of the anomalously high Sr isotopic compositions obtained for these rocks. Sr compositions have been altered from a primary value that ranged between 0.707-0.709, which represent typical Sr compositions of Late Proterozoic limestones (Veizer *et al.*, 1983) to a value of 0.734, and as such represents an extreme case of rock alteration by crustal fluids. Modeling water:rock ratios has been performed in the manner described by Banner and Hanson (1990). A brief summary of the equations used in the model is given below.

For conditions of chemical equilibrium between the fluid and the rock, the exchange distribution coefficient, $K_D{}^{Sr\text{-}Ca}$ is defined as

$$K_D{}^{Sr\text{-}Ca} = \frac{C_S{}^{Sr}/C_f{}^{Sr}}{C_S{}^{Ca}/C_f{}^{Ca}} \qquad (1)$$

where C_s and C_f are the concentrations in ppm of the element in the solid and fluid, respectively. K_D for the Sr-Ca pair ranges from 0.05 to 0.14 (Veizer *et al.*, 1983). The strontium concentration in the fluid-rock system is defined initially as

$$C_o{}^{Sr} = F{*}C_f{}^{Sr}+(1-F){*}C_s{}^{Sr} \qquad (2)$$

where F = weight fraction (ppm) of fluid in the system. The concentration of Sr in the rock is then calculated by:

$$C_s{}^{Sr} = \frac{C_o{}^{Sr}}{F/D^{Sr}+(1-F)} \qquad (3)$$

where the Sr distribution coefficient $D^{Sr} = C_S{}^{Sr}/C_f{}^{Sr}$. This concentration is then used to recalculate $C_o{}^{Sr}$ in equation (2).

The simultaneous changes in the Sr isotopic composition of the limestone is calculated by:

$$({}^{87}Sr/{}^{86}Sr)_o = \frac{(C_f{}^{Sr})F(Sr_f{}^*)+(C_s{}^{Sr})(1-F)(Sr_s{}^*)}{C_o{}^{Sr}} \qquad (4)$$

where $Sr_f{}^*$ and $Sr_s{}^*$ = $^{87}Sr/^{86}Sr$ values of the fluid and limestone respectively.

Cumulative water/rock ratios at any point is given by:

$$N=n{*}(F/(1-F)) \qquad (5)$$

where n= number of iterations. With each iteration, the computed water:rock ratio implies complete interaction and equilibration between the solid and the fluid (Banner and Hanson, 1990). Equations 1-5 were run using a BASIC program, listed in Appendix III. The values used in the equations are shown in Table 7.

Table 7 Parameters used in water/rock calculations

Phase	Concentration (ppm)	Phase	$^{87}Sr/^{86}Sr$
C_f^{Ca}	5000	Sr_f^*	0.770
C_S^{Ca}	400,000	Sr_s^*	0.707
C_f^{Sr} (calculated)	139		
C_S^{Sr}	280		

The two Miette limestones have an average $^{87}Sr/^{86}Sr$ value of 0.734. This represents the final isotopic composition of the limestones. The original Sr isotopic composition of these limestones is estimated to be 0.707 since unaltered Proterozoic limestones typically have $^{87}Sr/^{86}Sr$ values of 0.707-0.709 (Veizer *et al.*, 1983), as mentioned above. Because there is no isotopic fractionation in $^{87}Sr/^{86}Sr$ during precipitation of calcite from a fluid (Faure, 1986), the $^{87}Sr/^{86}Sr$ value of the veins represents the Sr value of the hydrothermal fluids. Consequently, the $^{87}Sr/^{86}Sr$ ratio in the fluids is estimated to range from 0.731 to 0.770.

Literature values for the Ca concentration of basinal brines range from 10,000 - 21,000 ppm (Gautier *et al.*, 1985; Hitchon *et al.*, 1971). Because the fluids are unlikely to be as saline as brines, a value of 5000 ppm is taken as an upper limit on C_f^{Ca}. This will provide a lower limit on the water:rock ratio of the system. The concentration of Ca in limestones (C_s^{Ca}) is 4^*10^5 ppm (Veizer, 1983). The changes in the Sr concentrations and $^{87}Sr/^{86}Sr$ ratios of the limestones from an initial value of 0.707 to a final value of 0.734 were calculated and plotted against cumulative water/rock ratios (Figure 16).

Using the maximum fluid $^{87}Sr/^{86}Sr$ ratio (0.770), the cumulative water:rock ratio lies between 0.5 (K=0.05) and 1.5 (K=0.14). These results

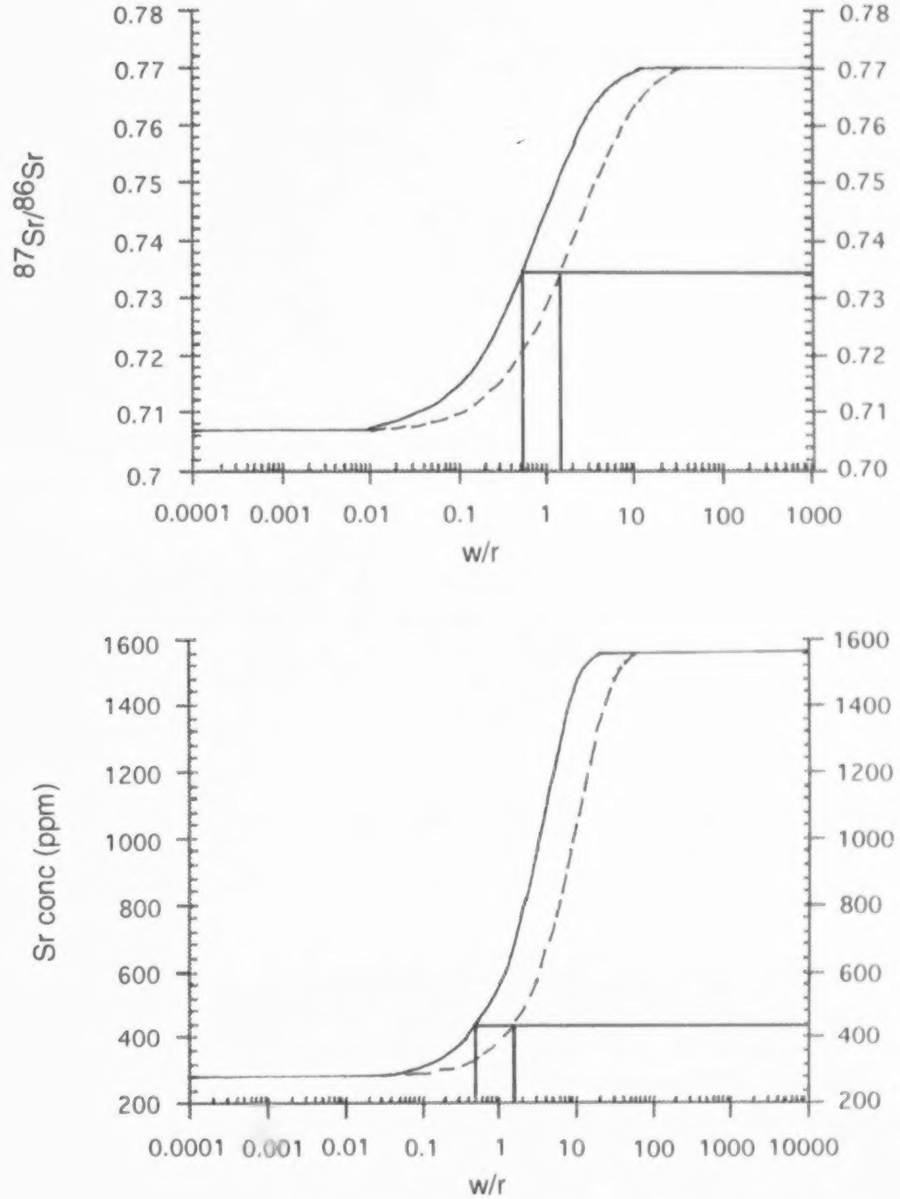

Figure 16 Water/rock ratios necessary to reset the limestone Sr ratio from 0.707 to a maximum of 0.770, and the Sr concentration from 280 to 1593 ppm. K=0.05 (solid line), K=0.14 (dashed line), Ca conc in fluid=5000 ppm. A water/rock ratio between 0.5 and 1.5 is needed to reset the limestone to its present value of 0.734 and 426 ppm. Equilibrium occurs at a w/r ratio of 20.

indicate that the minimum water:rock ratio involved in this system, which involves the interactions between the limestone beds within the Miette Group and a saline fluid rich in Sr, ranges from 0.5-1.5. These water:rock ratios, although not large, are suggested to represent the water:rock ratios that were involved in altering the strontium isotopic ratios in the limestone when it interacted with a highly radiogenic fluid.

Finally, it should be noted that this system has not yet reached isotopic equilibrium. The final Sr ratio of the limestones (0.734) is still less than the Sr ratio of the fluid (0.770). Similarly, the final Sr concentration of the limestones (426 ppm) is less than the Sr concentration of the fluid (1593 ppm) in equilibrium with the veins. Had the system equilibrated, the water:rock values would also have been higher. From Figure 16 it can be seen that chemical equilibrium would have occurred at a water:rock ratio of approximately 20.

D. Fluid Mixing

Mixing relations have been investigated in the vein carbonates sampled in the Intermontane belt. The high Sr isotopic compositions obtained for calcite veins indicate a component from the host volcanic rocks, but also suggest an additional source of strontium. If the volcanic rocks hosting the vein carbonates have interacted with fluids having a strontium ratio derived from an external, possible sedimentary source, it is reasonable to assume that a mixing trend may be recorded in the chemical compositions of the vein carbonates (Figure 17).

Faure (1986) has discussed the relationship of mixing two components having different isotopic compositions and concentrations. By plotting $^{87}Sr/^{86}Sr$ versus the reciprocal of Sr concentrations (in ppm), a straight line is obtained if mixing between the two components has occurred. This technique has been applied to river waters (eg. Fisher and Stueber, 1976), and subsurface waters and brines (eg. Connolly *et al.*, 1990). Others have attempted to determine mixing relations between hydrothermal fluids and adjacent wall rocks with limited success (eg. Mueller *et al.*, 1991; King and Kerrich, 1989; Farmer and DePaolo, 1987; Lange *et al.*, 1983). In this study, it is suggested that a mixing trend may be evident between the fluids derived from limestones and the host volcanics in the autochthonous terranes of the

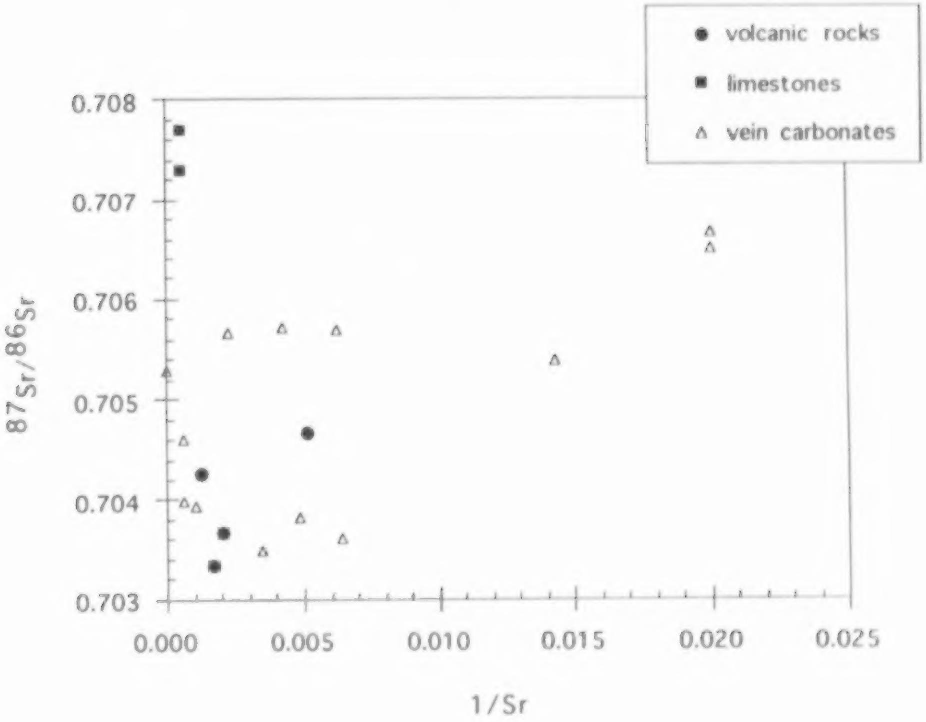

Figure 17 Plot of $^{87}Sr/^{86}Sr$ versus 1/Sr for vein carbonates from the Intermontane belt. Data for volcanic host rocks and limestones are from Smith (1986) and Faure (1986) respectively.

southern Canadian Cordillera. Average concentrations and the $^{87}Sr/^{86}Sr$ ratios for Triassic and Late Cretaceous limestones, representing limestones of the Nicola and Spences Bridge Groups (0.7073-0.7077), and are estimated from Faure (1986) and Burke *et al.*, (1982), to represent average chemical characteristics of the limestones in the region. Initial $^{87}Sr/^{86}Sr$ ratios for the volcanic rocks of the Nicola, Spences Bridge, Cache Creek and Kamloops Groups (0.7033-0.7047) are from Smith (1986). Clastic rocks associated with the volcanic rocks may be a possible source of Sr to the vein-forming fluids. Sr isotopic compositions of clastic rocks are estimated to range from 0.705 and 0.709, based on the measured Sr values of shales and the likely source of the detrital minerals in this region. The Sr concentrations can range from 20-200 ppm (Faure, 1986). Because the compositions can not be tightly constrained, this rock type was not plotted on Figure 17.

There appears to be a mixing trend of strontium isotopic compositions between the volcanic rocks and the marine limestones on Figure 17; however, there is no evidence of mixing of the Sr concentrations between these two sources. The vein carbonates have isotopic and chemical compositions that correlate to some degree with the volcanic host rocks. The scatter in Figure 17 suggest that an external source exists. A sedimentary source for the strontium in the calcite veins can not be ruled out.

E. Hydrothermal Fluid Flow: Alteration of Sr Isotopic Compositions

A question fundamental to this study concerns how far fluids travel through rock units while maintaining their strontium isotopic signature. The rate to which chemical equilibrium is reached between the fluids and rocks that are encountered along migration pathways will have a bearing on the ability of the fluid to preserve its isotopic characteristics. As mentioned earlier, the rate at which isotopic equilibrium is reached between fluids and host rocks depends on a variety of factors, including the isotopic characteristics of the fluid and the wall rock, and whether the fluid flow is channelized through large faults or pervasive through rock units. The preservation of the strontium systematics in mineralizing fluids has been addressed by various authors including Böhlke and Kistler, (1986), Norman and Landis (1983), Kerrich *et al*, (1979), and Farmer and DePaolo, (1987).

Böhlke and Kistler (1986), in their study of gold-bearing quartz veins in the Sierra Nevada Foothills, California, examined strontium ratios of the metasomatic fluids and reported large regional variations ($^{87}Sr/^{86}Sr$ of 0.704-0.718) that correlate broadly with the strontium ratios of regional lithologies exposed within the mining districts. They estimated a distance of 1 to 2 km for the fluids to equilibrate with the rocks near the mined portion of the veins.

Norman and Landis (1983) traced the source of hydrothermal fluids in the W-Cu-Ag-Pb-Zn quartz veins in the Pasto Bueno deposit, Peru. $^{87}Sr/^{86}Sr$ values of veins range from 0.7059 to 0.7208. The host rocks of the Consuzo stock range from 0.7056 to 0.7074. They estimated that to produce the higher vein Sr ratios, fluids had carried the strontium signature from the underlying metamorphosed basement rocks through the stock for several kilometers without reaching isotopic equilibration with the plutonic wall rocks.

Kerrich *et al.* (1979) have documented Sr isotopic compositions of hydrothermal minerals associated with large transcurrent faults in Archean mesothermal gold deposits in the Abitibi greenstone belt. They noted a lack of correlation of initial Sr ratios between the minerals and the immediate host lithologies within the fault zones. The tight clustering of Sr ratios within different domains indicated uniform Sr ratios for distances of approximately one kilometer.

Sr isotopic compositions of hydrothermal fluids associated with the San Manuel porphyry copper deposit in Arizona were used to determine the extent of isotopic exchange between mineralized monzogranite porphyry (0.708) and the Precambrian Oracle granite (0.782) which hosted the monzogranite (Farmer and DePaolo, 1987). The altered wall rock of the granite showed an increase in $^{87}Sr/^{86}Sr$ with increasing distance from the porphyry. These ratios were preserved for a distance of 750 meters into the granite.

This study has documented several occurrences of Sr isotopic disequilibrium. The Paleozoic limestone sequences of the Rocky Mountains document the largest distance of preservation of strontium compositions of fluids. Saline fluids (preorogenic fluid event) caused oxygen isotopic alteration in Cambrian limestones over distances of hundreds of square kilometers (Nesbitt *et al.*, 1993). Because of the high concentration of Sr in these fluids, the strontium isotopic signatures record alteration of limestones for distances of similar size. Pervasive fluid flow from the westerly shale sequences through the easterly limestone rocks has reset the Sr compositions of the limestone units from 0.7089-0.7091 to 0.7096-0.7101.

A second occurrence of isotopic disequilibrium involves the vein carbonates hosted by volcanic rocks of the Spences Bridge, the Kamloops and the Cache Creek Groups in the Intermontane belt. Calcite veins are characterized by $^{87}Sr/^{86}Sr$ values that have been derived in part from the volcanic host rocks and in part from an external, possibly sedimentary source.

F. Future Work

This study has provided a broad overview of the Sr isotopic characteristics of vein carbonates associated with hydrothermal systems across the southern Canadian Cordillera. However, detailed investigations of the hydrothermal systems in areas where the isotopic data was inconclusive are recommended. These areas include the Slocan region to the north of the Nelson batholith and the Phoenix-Greenwood district in the Omineca belt. Specifically, a detailed study of the veins and replacement minerals in the Phoenix Cu-Au skarn deposit would help to decipher the complex fluid pathways in this hydrothermal system.

Secondly, the mesothermal gold deposits in the Cariboo district appear to contain anomalous $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values in relation to the regional barren veins. However, no isotopic analyses of the limestones hosting the mineralized veins were conducted. A detailed stable and radiogenic isotopic study of the mineralized veins and host rocks of the Cariboo district is recommended in order to determine the source of the strontium and carbon in the vein-forming fluids. In addition, isotopic studies in other mesothermal gold deposits in the Canadian Cordillera would further constrain the source of the hydrothermal fluids involved in these systems.

The Sr isotopic variation found within individual veins in this study was large in some cases. In order to determine whether the heterogeneity is the result of local variations in Sr isotopic compositions of host rocks, or the result of different generations of fluid, recognition of zoning during calcite growth within the vein is essential. Cathodoluminescence analyses in addition to mineralogical and textural studies would indicate the presence of multiple generations of calcite within a vein. Conducting a detailed Sr isotopic study across a vein and into the contiguous host rock would yield further insights into the changes in Sr isotopic compositions that exist at this scale.

Lastly, it is recommended that future sampling be done in areas such as in the region to the west of the Rocky Mountain Trench, and in the Purcell Anticlinorium. These Proterozoic units will further delineate the regional transitions in $^{87}Sr/^{86}Sr$ of vein carbonates within the Canadian Cordillera.

VIII. SUMMARY

A systematic study of the Sr, O, and C isotopic characteristics of vein carbonate across the southern Canadian Cordillera has documented fluid/rock interaction between hydrothermal carbonates and host rocks. Five general conclusions can be made.

1) Vein carbonates display large heterogeneity in Sr isotopic compositions in regions where veins are hosted by old sialic crustal rocks. For example, $^{87}Sr/^{86}Sr$ values from 0.731 to 0.774 occur in vein carbonates of the Proterozoic Miette Group in the Rocky Mountains. In contrast, the $^{87}Sr/^{86}Sr$ values are more homogeneous in veins that are hosted by relatively younger (Mesozoic-Cenozoic) rocks derived from mantle sources. The variations typically range between 0.705-0.707 for volcanic-hosted vein calcites in the Intermontane belt.

2) Vein carbonates display a geographic variation in $^{87}Sr/^{86}Sr$ values across the southern Canadian Cordillera that decrease from east to west. Vein carbonates in the Proterozoic sequences in the Rocky Mountain Belt have Sr isotopic ratios that are > 0.730 and have been documented to be as large as 0.774. In the eastern portion of the Omineca belt, the Sr isotopic ratios range from 0.709 to 0.738. Vein carbonates have $^{87}Sr/^{86}Sr$ values falling between 0.705 to 0.707 in the Intermontane belt and the western portion of the Omineca belt. The abrupt change in Sr isotopic compositions approximately coincides with the north-south trending Slocan Fault and its northern equivalent, the Columbia River Fault. Further west, the Fraser Fault region exhibits Sr ratios that are < 0.705. The east-west gradient is probably a direct reflection of the changing lithology of crustal rocks, from a carbonate dominated regime with older sialic rocks in the eastern section to an increasingly younger volcanic regime in the west.

3) The variation in $\delta^{18}O$ values of vein carbonates fluctuate across the southern Cordillera and do not correlate with the changes observed in the Sr isotopic compositions. The lowest $\delta^{18}O$ values are observed in the Intermontane Belt while higher values occur in the Rocky Mountains and to the

west of the Fraser fault zone. Similarly, vein carbonates do not show a sympathetic variation in $\delta^{13}C$ in relation to the $^{87}Sr/^{86}Sr$ ratios. Large variations in carbon isotopic compositions occur within regions that have homogeneous Sr isotopic compositions. Consequently, the $\delta^{13}C$ values are inherited compositions obtained by water-rock interaction of vein-forming fluids with local sources.

4) In the Rocky Mountains, the fluid regimes defined by Nesbitt *et al.* (1993) are also distinct in Sr isotopic compositions. The Sr isotopic compositions of carbonate rocks formed from preorogenic fluids range from 0.7092 to 0.7119. The resetting of the Sr isotopic system in the Paleozoic carbonate lithologies and replacement minerals on a scale of 100's of square kilometres indicates that the pervasive flow of saline fluids have caused large scale alteration throughout the Paleozoic units. Carbonate vein-forming fluids associated with the syn- to postorogenic fluid event have $^{87}Sr/^{86}Sr$ ratios of 0.7091 to 0.7093 and 0.7309 to 0.7741 within the Paleozoic units and Proterozoic units, respectively.

5) Large variations are present in the $^{87}Sr/^{86}Sr$ isotopic compositions within the vein carbonates of the Cariboo ($^{87}Sr/^{86}Sr = 0.7111 - 0.7217$) and Sheep Creek ($^{87}Sr/^{86}Sr = 0.7109 - 0.7214$) mesothermal gold deposits. This heterogeneity is interpreted to indicate that either the compositions of the vein-forming fluids were not uniform during the time of mineralization or local heterogeneity is present in the wall rocks of the ore deposits. Furthermore, in the Cariboo district, the Sr isotopic compositions of the mineralized vein carbonates are highly radiogenic relative to the regional barren veins, which have $^{87}Sr/^{86}Sr$ values ranging from 0.7088 to 0.7096. $\delta^{18}O$ and $\delta^{13}C$ values also differ between the mineralized and unmineralized veins in this region. In contrast to the mesothermal gold deposits, the isotopic data from the epithermal gold deposit in the Vault property indicate that the vein-forming fluids have incorporated strontium and carbon from host volcanic rocks.

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Appendix I. XRF Analyses

Sample	Rock Type	Sr ppm	Rb ppm	Ca %	Mg %	Fe %	Mn %
AK91-1	phyllite	926, 796	0	50.029	0.350	1.050	0.174
AK91-2	mudstone	898	0	58.427	0.228	0.856	0.041
AK91-3	mudstone	1854	0	64.075	0.270	0.393	0.042
AK91-4	phyllite	1051	0	40.814	0.319	1.392	0.103
AK91-5	phyllite	698	0	62.934	0.905	2.588	0.345
AK91-6	slate	1693	0	46.629	0.119	0.825	0.157
AK91-7	limestone	1010	0	22.681	0.055	0.849	0.191
AK91-7a	**limestone**	5110	120	36.596	1.506	7.706	0.475
AK91-9	limestone	37	0	65.917	0.143	1.425	0.047
AK91-10	volcanic	37	0	59.618	0.271	0.786	1.634
AK91-11	volcanic	246	0	64.922	0.227	1.153	1.347
AK91-12	mudstone	1043	0	55.387	0.224	1.439	0.700
AK91-13	schist	1132	0	54.224	0.162	0.453	0.339
AK91-14	schist	1127	0	42.842	0.422	2.963	0.444
AK91-15	schist	102	0	43.914	0.122	0.854	0.218
AK91-16	mudstone	1848	0	64.811	0.313	2.093	0.283
AK91-17	mudstone	1331	0	53.027	0.210	1.237	0.399
AK91-18	mudstone	169	0	20.239	0.194	0.634	0.074
AK91-19	shale	1243	0	64.879	0.094	0.633	0.337
AK91-20		207	0	13.150	0.074	1.060	0.155
AK91-21	volcanic	0	0	66.596	0.000	0.029	0.021
AK91-22	volcanic	292	0	58.933	0.041	0.033	0.412
AK91-23	volcanic	156	0	50.955	0.072	0.709	0.094
AK91-24	greenschist	1230	40	39.710	0.092	0.536	0.461
AK91-25	greenschist	160	0	11.935	0.060	0.777	0.281
AK91-26	greenschist	454	0	58.096	0.116	0.294	0.387

Sample	Rock Type	Sr ppm	Rb ppm	Ca %	Mg %	Fe %	Mn %
AK91-27	limestone	836	0	52.028	0.208	0.872	0.297
AK91-27a	**limestone**	1960	80	20.126	0.733	3.991	0.175
AK91-28	mudstone	1567	0	38.837	0.437	1.091	0.239
AK91-29	limestone	1219	0	27.370	7.922	4.358	0.817
AK91-30	mudstone	985	0	29.897	0.055	0.504	0.144
AK90-7	slate	111	0	13.869	0.317	7.481	0.260
AK90-8	phyllite	700	0	7.496	0.099	0.675	0.119
AK90-9	phyllite	618	0	26.988	0.056	0.460	0.121
AK90-13	siltstone	3964	0	52.462	0.284	1.126	0.098
AK90-14	siltstone	324	0	33.463	2.430	4.497	0.178
AK90-18	siltstone	2304	0	64.621	0.314	0.477	1.258
AK90-19							
AK90-20	granodiorite	887	0	68.232	0.075	0.501	0.613
AK90-21	granodiorite						
AK90-22		376	0	62.042	0.105	0.512	1.460
AK90-23		760	10	50.929	0.098	0.598	0.266
AK90-24			0	8.648	0.112	3.533	0.092
AK90-25		994	0	70.726	0.101	0.734	0.714
AK90-36	mudstone	0	0	5.619	0.354	0.844	0.055
AK90-38	volcanic						
AK90-43	volcanic	59	0	13.622	0.065	0.513	0.028
RB 563		166	0	16.962	0.088	0.781	0.193
RB 569		691	0	42.703	0.152	0.775	0.223
RB 570	quartzite						
RB 573	shale	653	0	10.243	0.034	0.700	0.238
RB 576							
RB 604	phyllite						
RB 624	dolomite						
RB 625	**dolstone**	150	40	40.608	10.815	1.461	0.091

Sample	Rock Type	Sr ppm	Rb ppm	Ca %	Mg %	Fe %	Mn %
RB 636	slate	39	0	9.047	1.507	4.220	1.881
RB 639		1593	0	18.881	0.072	0.850	0.167
RB 641		1154	0	53.522	0.253	1.889	0.511
RB 659	**limestone**						
RB 662	slate	6151	0	45.286	2.083	2.023	0.021
RB 671							
RB 678	limestone	890	0	56.097	1.190	0.311	0.000
RB 695	**limestone**	213	0	51.366	4.753	0.380	0.042
RB 706	**limestone**	1798	0	52.947	1.896	0.481	0.006
RB 710	**limestone**	372	0	64.018	0.502	0.028	0.000
RB 732	**dol. breccia**	27	0	37.350	11.431	3.906	0.232
RB 733	**dol. breccia**	80	0	39.162	12.597	4.888	0.376
RB 754	**limestone**	408	0	50.776	0.564	1.390	0.117
RB 755	**limestone**	444	70	50.191	0.598	1.303	0.203
RB 810	**dolostone**						
RB 824	**magnesite**						
CR 13	limestone	337	0	64.953	0.438	6.698	1.666
NBS 88b	**Dol. lmst**	47, 30	0	39.478	11.717	0.381	0.021
SrCO3 1	calcite std	2048	0	57.271	0.027	0.000	0.000
SrCO3 2	calcite std	4767	0	58.161	0.028	0.000	0.000
SrCO3 3	calcite std	9146	0	61.628	0.016	0.000	0.000

Note: Bold indicates analysis of host rock
SrCO3 standards 1,2 and 3 are 1994 ppm, 4766 ppm and 9099 ppm, respectively

Appendix II.
Corrections for high Rb concentrations

Throughout this study, the assumption is made that the measured ^{87}Sr/^{86}Sr ratio of vein carbonate is the same as the initial ^{87}Sr/^{86}Sr ratio. This is valid in most cases because carbonates typically have low or negligible Rb concentrations. However, XRF analyses indicated that a few carbonates (both vein and host rocks) contain sufficient concentrations of Rb to make corrections to the ^{87}Sr/^{86}Sr ratio necessary.

The equations used to correct the measured ^{87}Sr/^{86}Sr value are presented. The elapsed time since vein formation and the Rb concentration will cause the initial Sr ratio to be lower than the measured ^{87}Sr/^{86}Sr ratio.

The relationship between $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_{meas}$ and $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_{init}$ is given by:

$$(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_{meas} = (^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_{init} + {}^{87}\mathrm{Rb}/^{86}\mathrm{Sr}\ (e^{\lambda t} - 1)$$

where $\lambda = 1.42 \times 10^{-11}$ and

t= time elapsed since formation of the vein.

If $^{87}\mathrm{Rb}/^{86}\mathrm{Sr}\ (e^{\lambda t}-1) > 0.00001$, then

$(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_{meas} - (^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_{init}$ is larger than 0.00001 and corrections are necessary.

^{87}Rb/^{86}Sr is dependent on the measured ^{87}Sr/^{86}Sr ratio and the Rb/Sr ratio by the relationship:

$$\frac{^{87}\mathrm{Rb}}{^{86}\mathrm{Sr}} = \frac{\mathrm{Rb}}{\mathrm{Sr}} * \frac{\mathrm{Ab}^{87}\mathrm{Rb}}{\mathrm{Ab}^{86}\mathrm{Sr}} * \frac{\mathrm{At\ wt\ Sr}}{\mathrm{At\ wt\ Rb}}$$

where Ab^{87}Rb and Ab^{86}Sr are the isotopic abundances of ^{87}Rb and ^{86}Sr, respectively and At wt Sr and At wt Rb are the atomic weights of Sr and Rb (Faure, 1986).

The following carbonate veins and rocks contained sufficient Rb for corrections to be made, given the approximate age of vein formation.

Sample[1]	**Rb/Sr**	**$^{87}Rb/^{86}Sr$**	**Maximum age**	**$(^{87}Sr/^{86}Sr)_{meas}$**	**$(^{87}Sr/^{86}Sr)_{init}$**
AK91-7a	0.0235	0.0681	~Eocene	0.70402	0.70400
AK91-24	0.0325	0.0941	~Eocene	0.70575	0.70572
AK91-27a	0.0408	0.1182	Eocene	0.70609	0.70606
AK90-23	0.0132	0.0382	Mesozoic	0.70648	0.70645
RB755	0.0530	0.1538	Tertiary	0.73558	0.73548

[1] Note: bold type indicates limestone; plain text indicates vein carbonate.

Appendix III.
Water/rock computer programme

```
REM SR EVOLUTION CALCULATIONS, USING THE METHOD OF BANNER AND HANSON, 1991
K#=.14
DIV#=1
NU#=1
DCA#=400000!/5000
DSR#=K#*DCA#
PRINT "DCA="DCA#
PRINT "DSR="DSR#

REM K#=DCA#/DSR#
PRINT "K="K#
CONCSRVEIN#=1564
POROSITY#=.01
CONCCAFLUID#=400000!/DCA#
CONCFLUID#=CONCSRVEIN#/DSR#
CONCSOLID#=280
COMPFLUID#=.77
COMPSOLID#=.707
DENFLUID#=1!
DENSOLID#=2.72
NUMBER#=1
FLUIDROCKRATIO#=0
OPEN "w/r" FOR APPEND AS #1
OPEN "conc" FOR APPEND AS #2
OPEN "ratio" FOR APPEND AS #3
PRINT "CALCULATION STARTED"

REM TO LIMIT CALCULATION
ENDCALC#=1E+07
DIVISIONS#=1000000!
DIVISION#=ENDCALC#/DIVISIONS#
DIVISION2#=DIVISION#

REM CALCULATION MODULE
F#=(POROSITY#*DENFLUID#)/(POROSITY#*DENFLUID#+(1-POROSITY#)*DENSOLID#)
FF#=F#/(1-F#)
F2#=1-F#
CNCFLUID#=CONCFLUID#*F#
CFLUID#=COMPFLUID#*CNCFLUID#
F3#=(F#/DSR#)+F2#
WRITE#1,FLUIDROCKRATIO#
WRITE#2,CONCSOLID#
WRITE#3,COMPSOLID#

WHILE ENDCALC#>NUMBER#
   CONCSYSTEM#=CNCFLUID#+F2#*CONCSOLID#
    COMPSYSTEM#=((CFLUID#)+(COMPSOLID#*CONCSOLID#*F2#))/CONCSYSTEM#
    CONCSOLID#=CONCSYSTEM#/(F3#)
   COMPSOLID#=COMPSYSTEM#
```

```
  FLUIDROCKRATIO#=NUMBER#*FF#
  IF NUMBER#=DIVISION# THEN
        NU#=  NU#+DIV#
        DIVISION#=DIVISION#+DIVISION2#*NU#
        WRITE#1,FLUIDROCKRATIO#
        WRITE#2,CONCSOLID#
        WRITE#3,COMPSOLID#
        FLUIDROCKRATIO=FLUIDROCKRATIO#
        CONCSOLID=CONCSOLID#
        COMPSOLID=COMPSOLID#
        PRINT FLUIDROCKRATIO,CONCSOLID,COMPSOLID
  END IF
  NUMBER#=NUMBER#+1
WEND
END
```